OLUME 102 PART A NUMBER 2 APRIL 1955

The Proceedings

OF

THE INSTITUTION OF ELECTRICAL ENGINEERS

FOUNDED 1871: INCORPORATED BY ROYAL CHARTER 1921

PART A

POWER ENGINEERING

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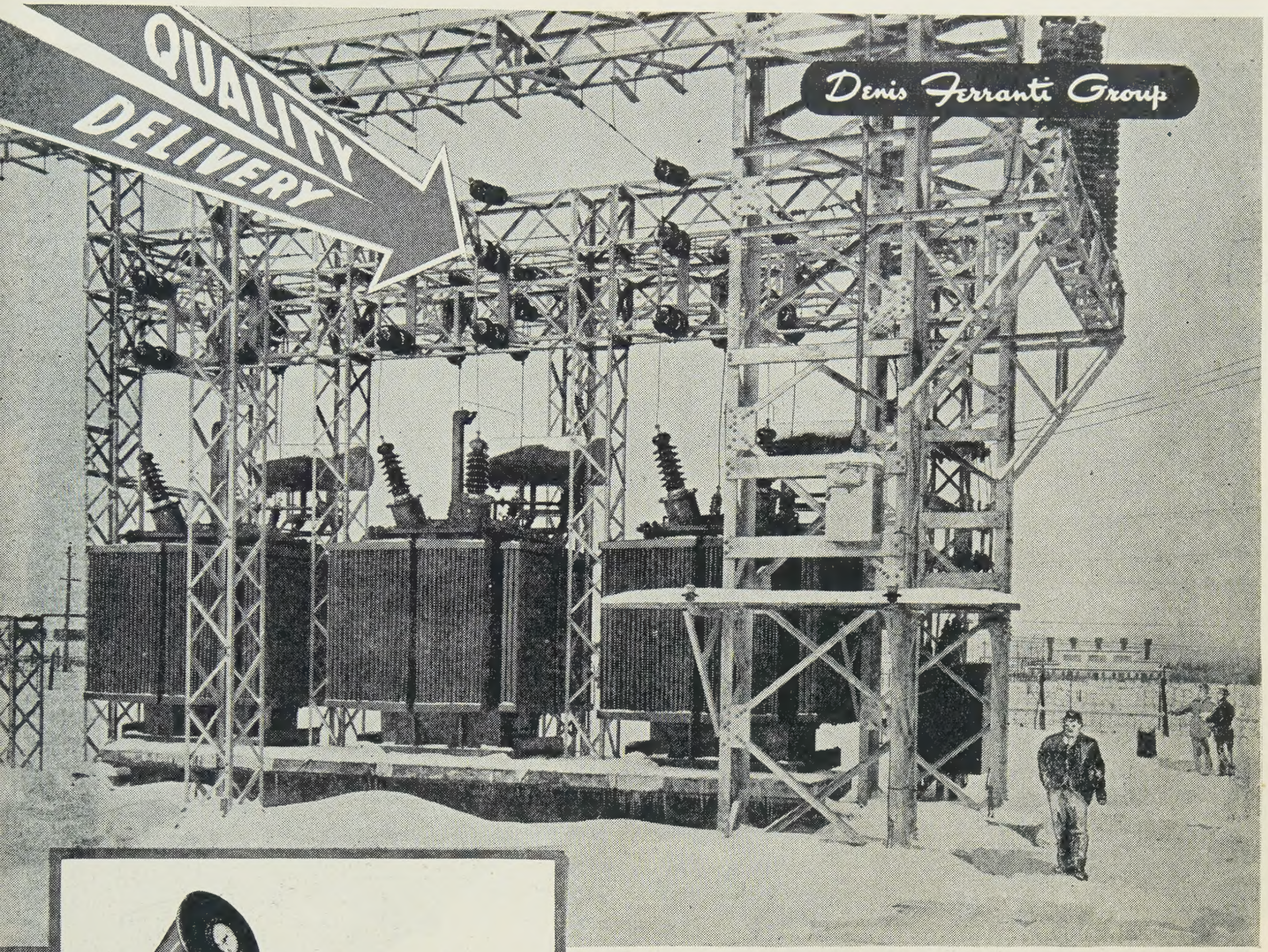

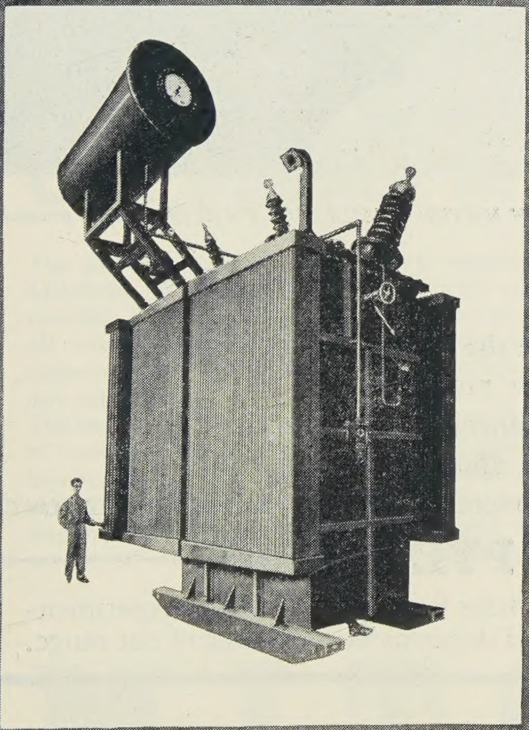

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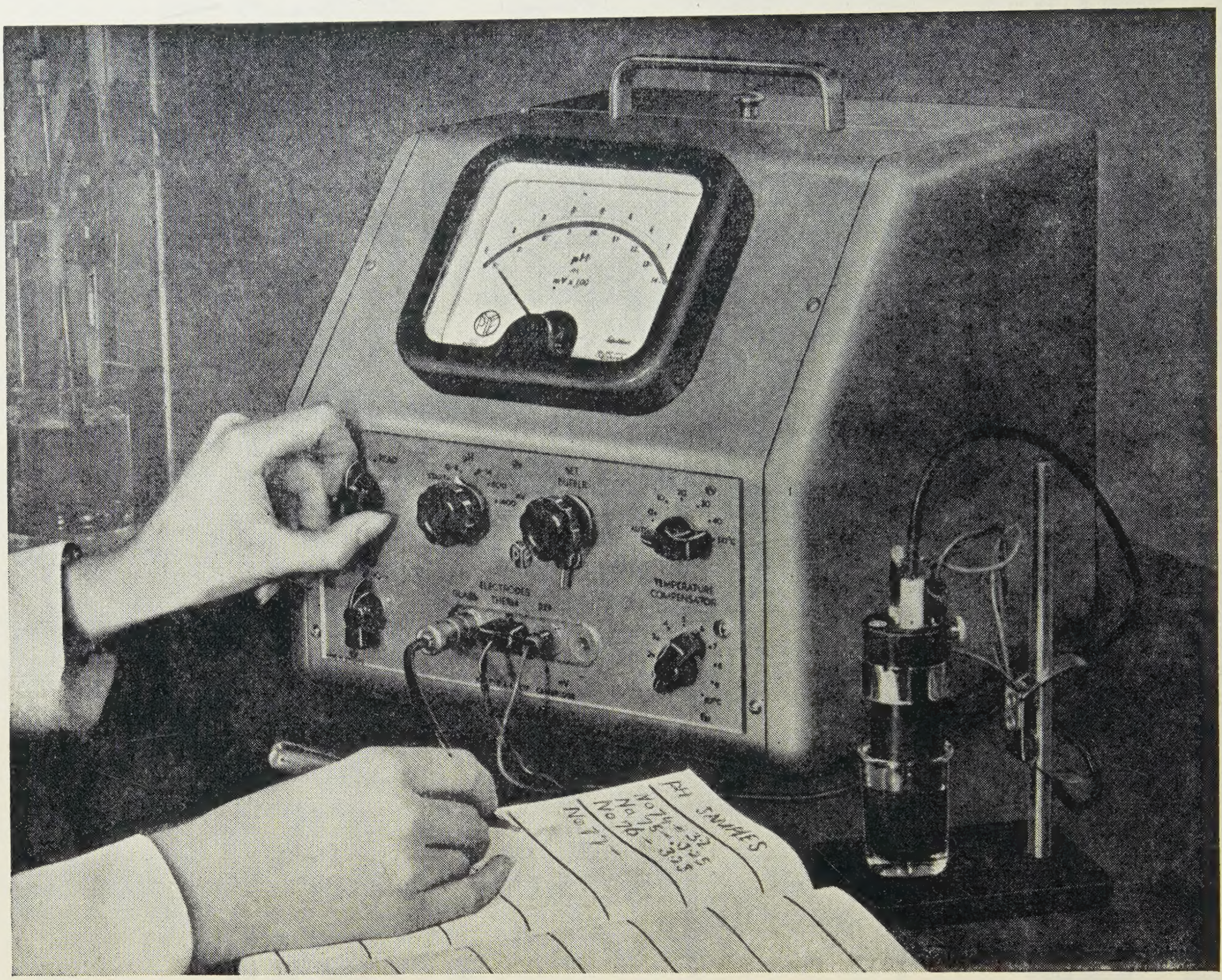

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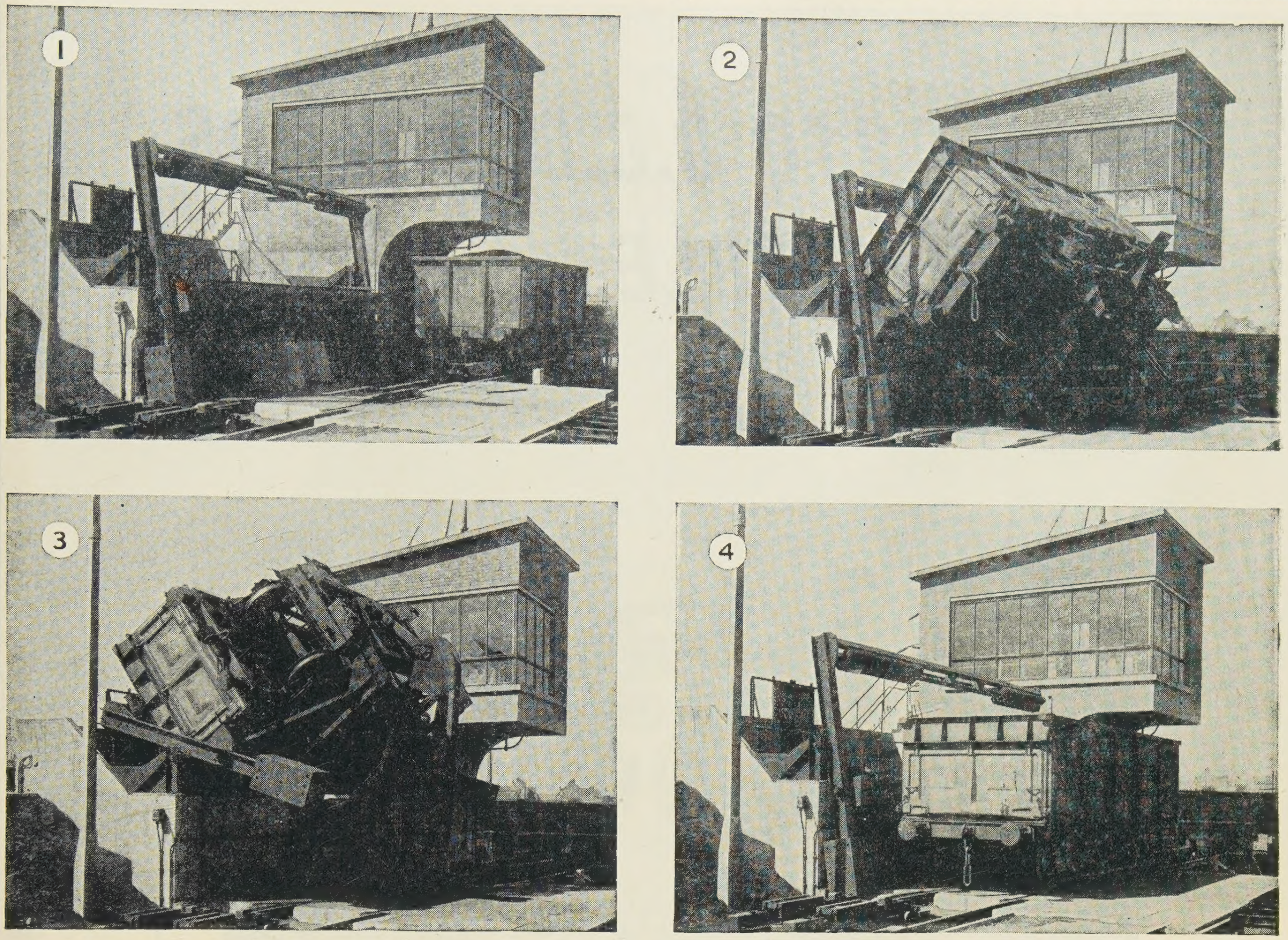

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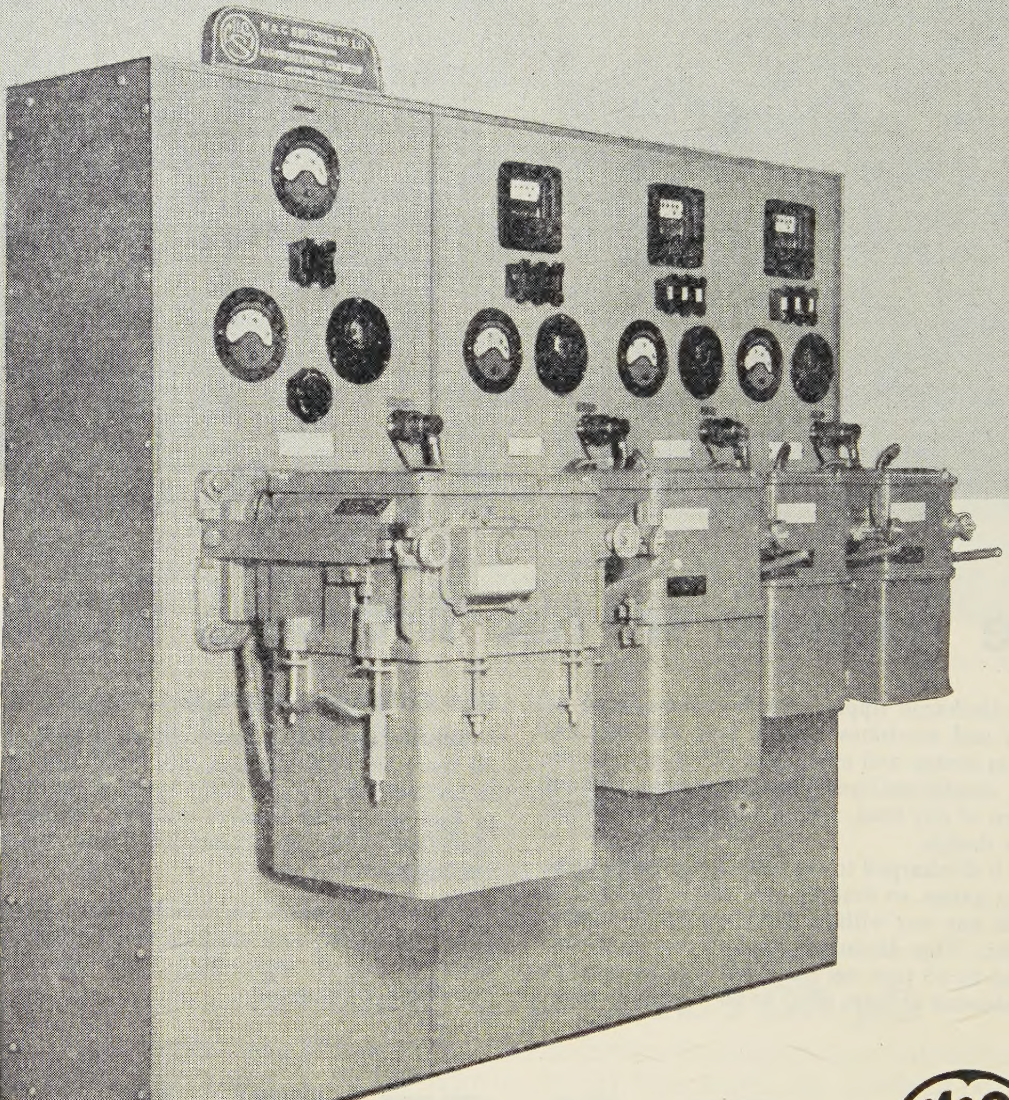

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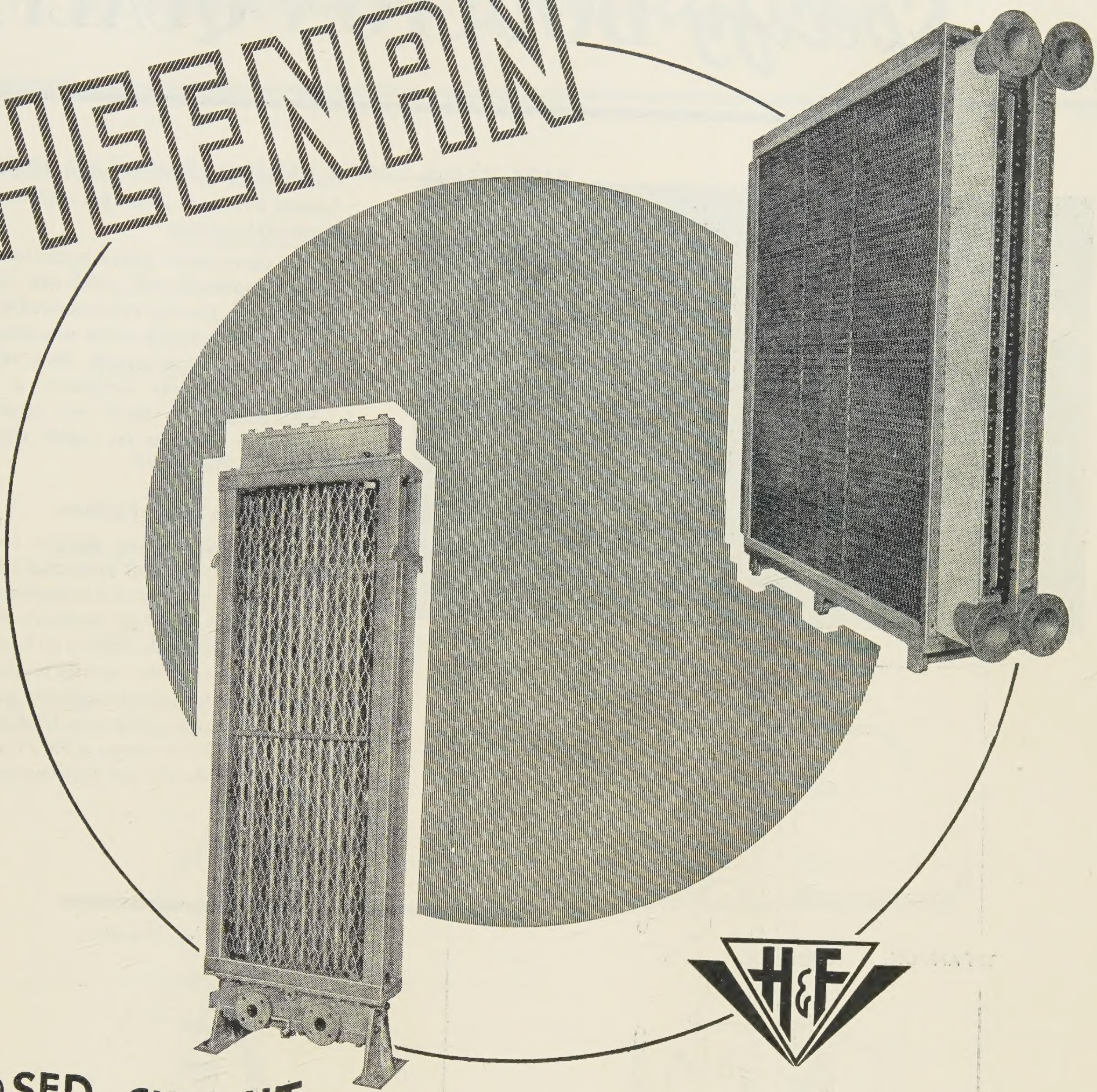

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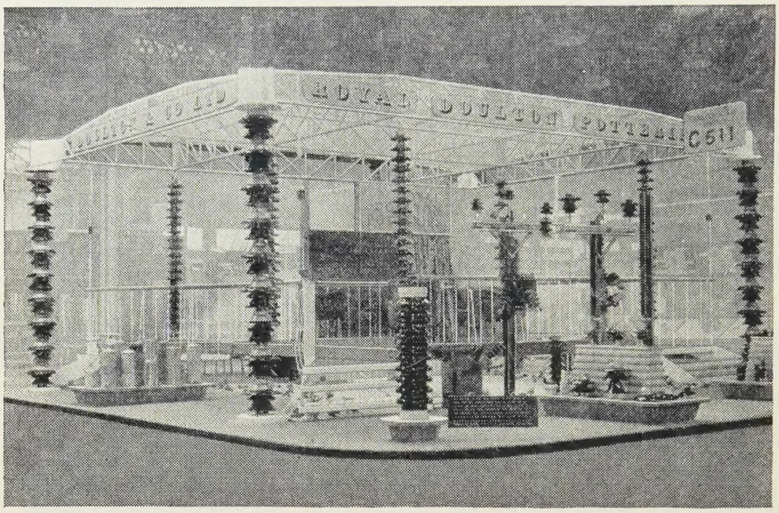

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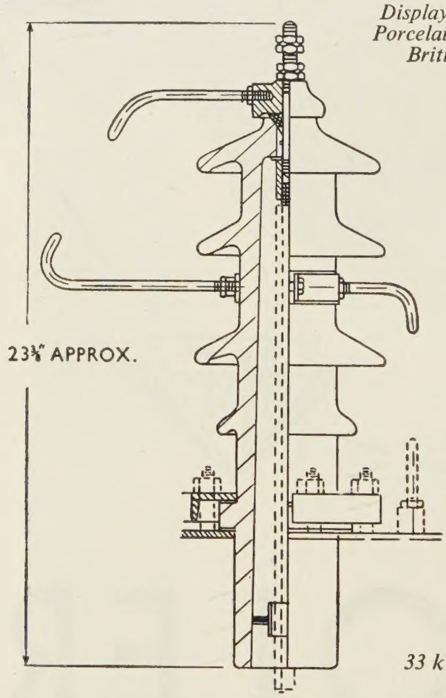

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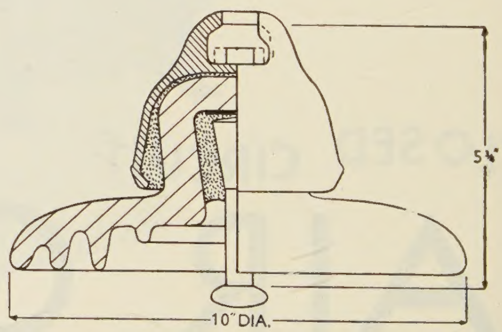

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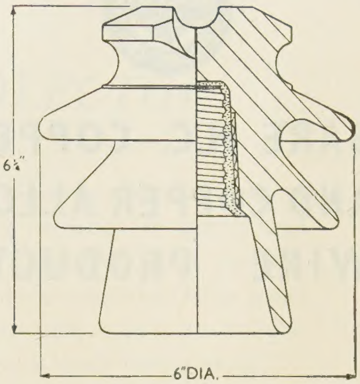

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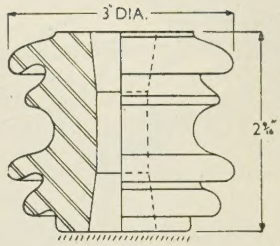

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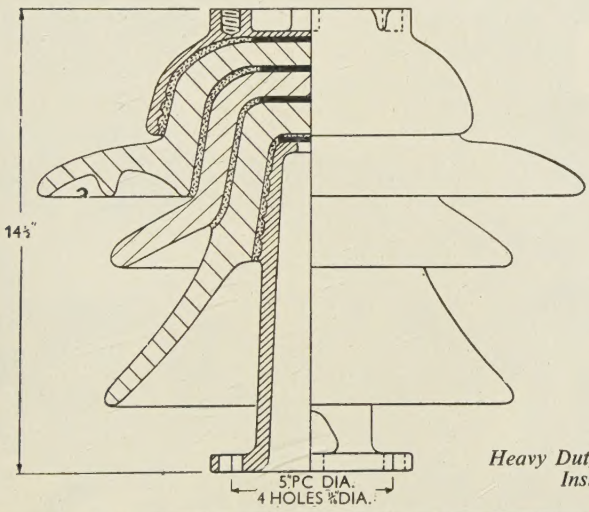

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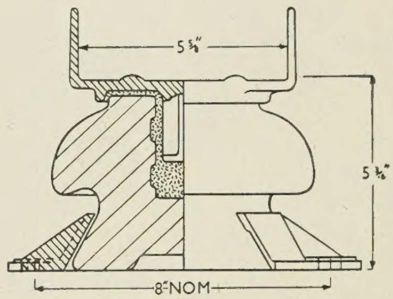

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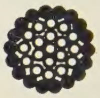

(*b*) 37 Tubular stranded.
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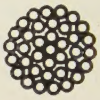

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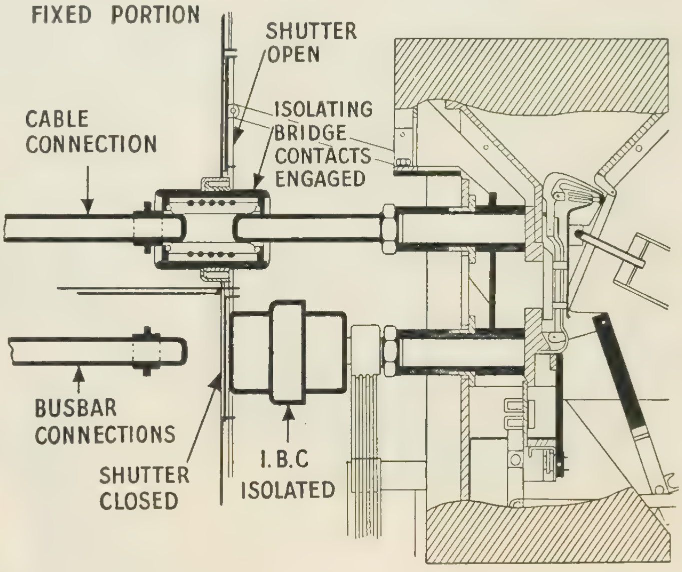

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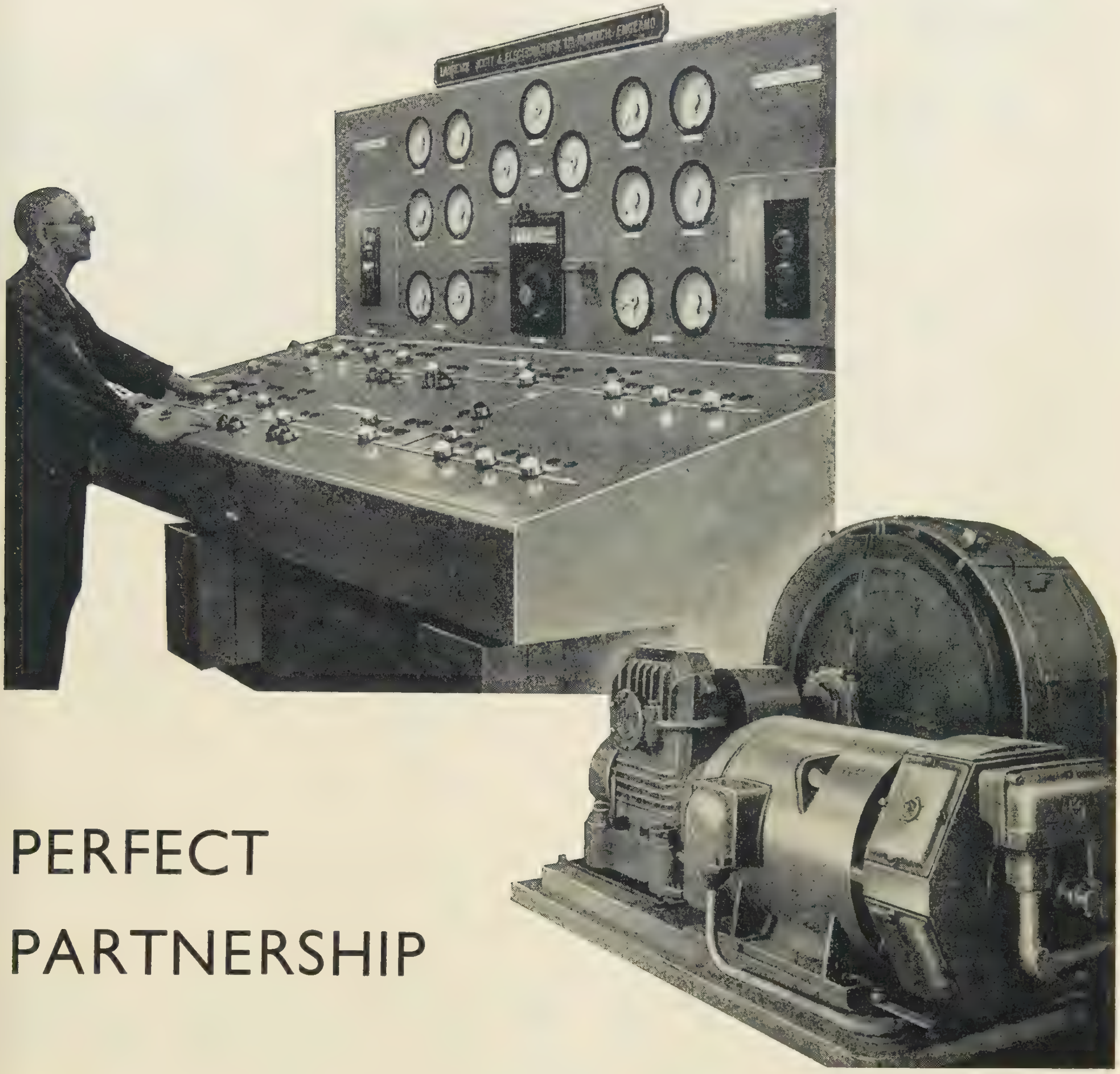

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Top illustration: Central control desk for diffuser main motors and ancillary motors in a British Sugar Corporation factory.

Lower illustration: N-S variable speed a.c. motor driving a beet cutter. An auxiliary 5 cycle supply from an N-S convertor provides very slow operation for the purpose of replacing knives, etc.

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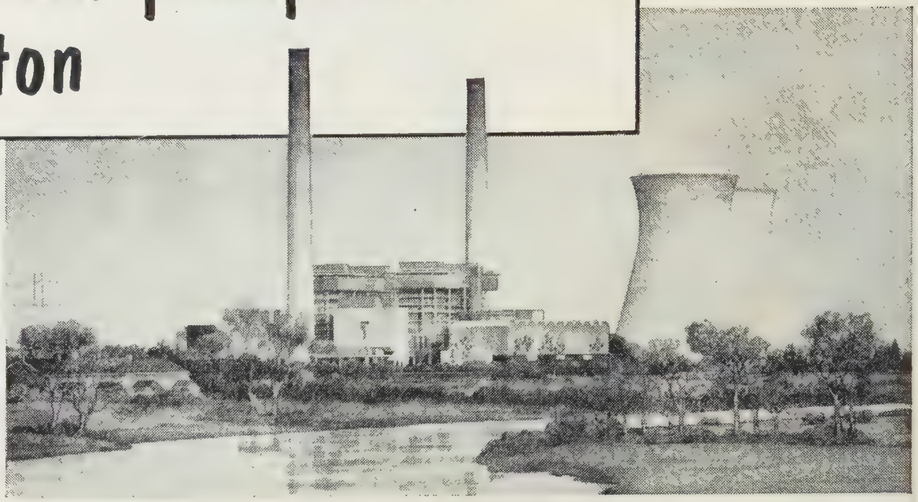

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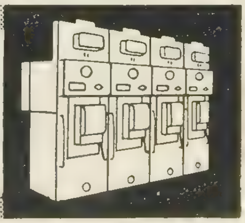

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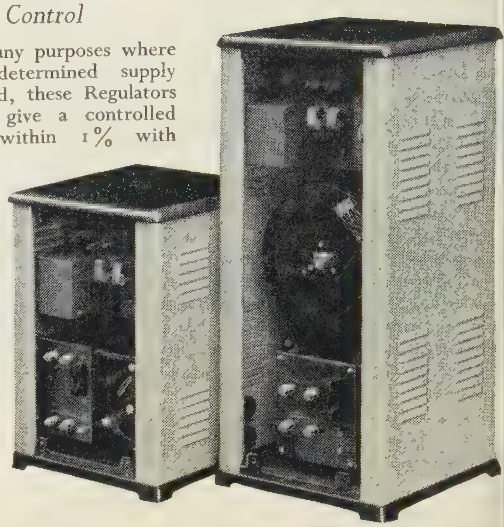

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7. Does the post involve the control of staff? If so, how many technicians and/or other workers?
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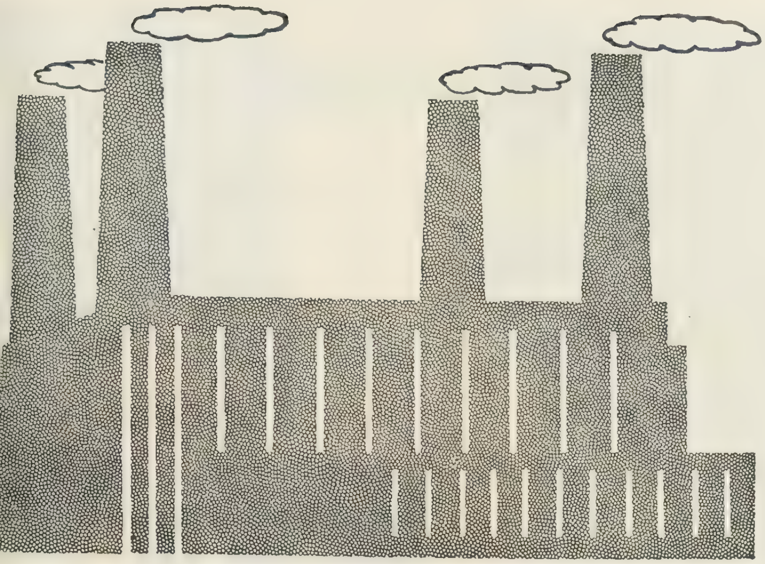

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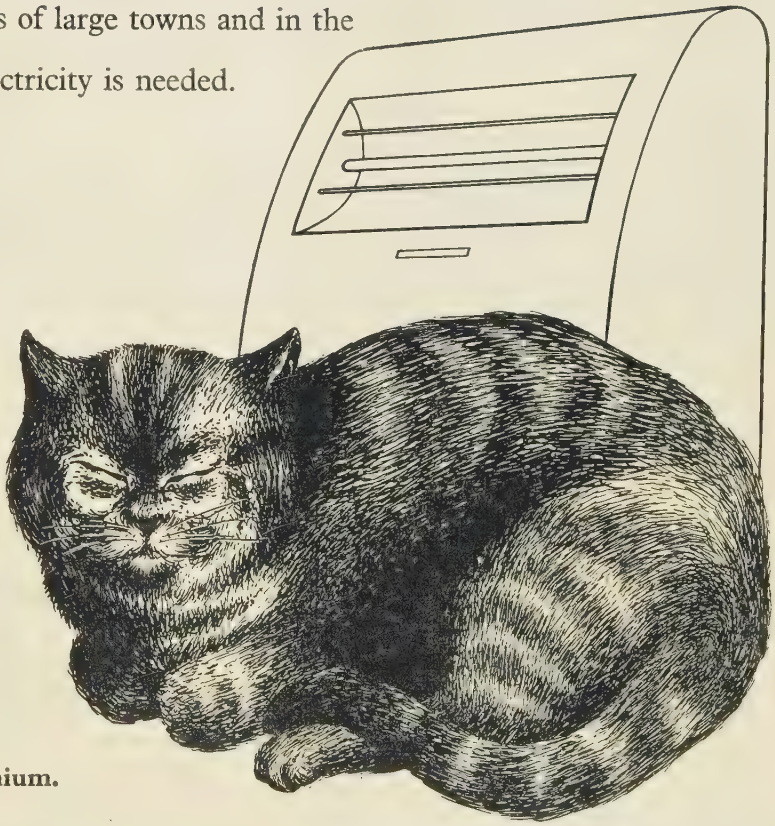

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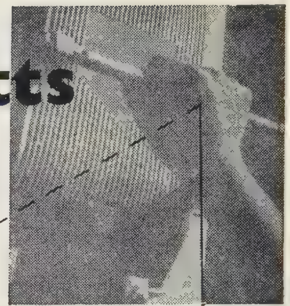

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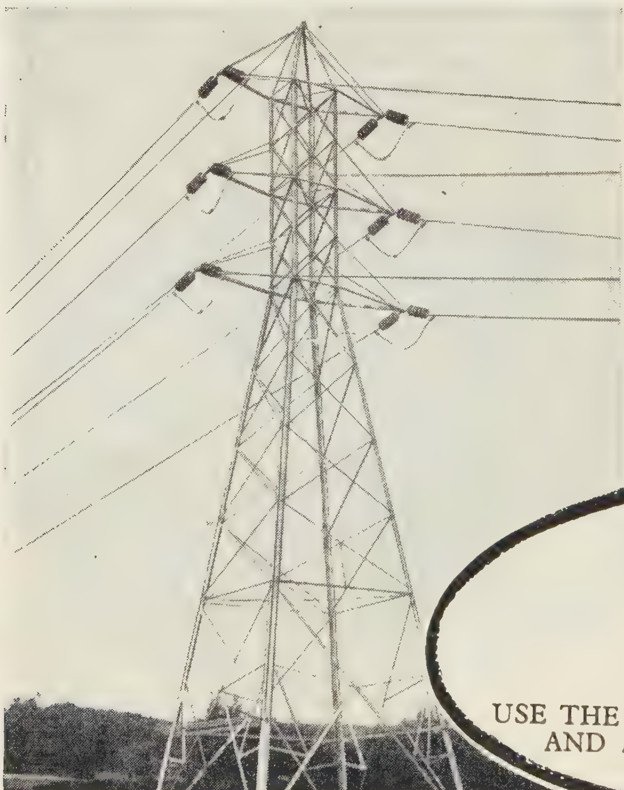

The photograph shows T.T. porcelain Cap and Pin Insulators on one of the first 66 kV Overhead Lines to be erected in the British Isles—a line from Maentwrog to Wrexham which is still in use after a quarter of a century.

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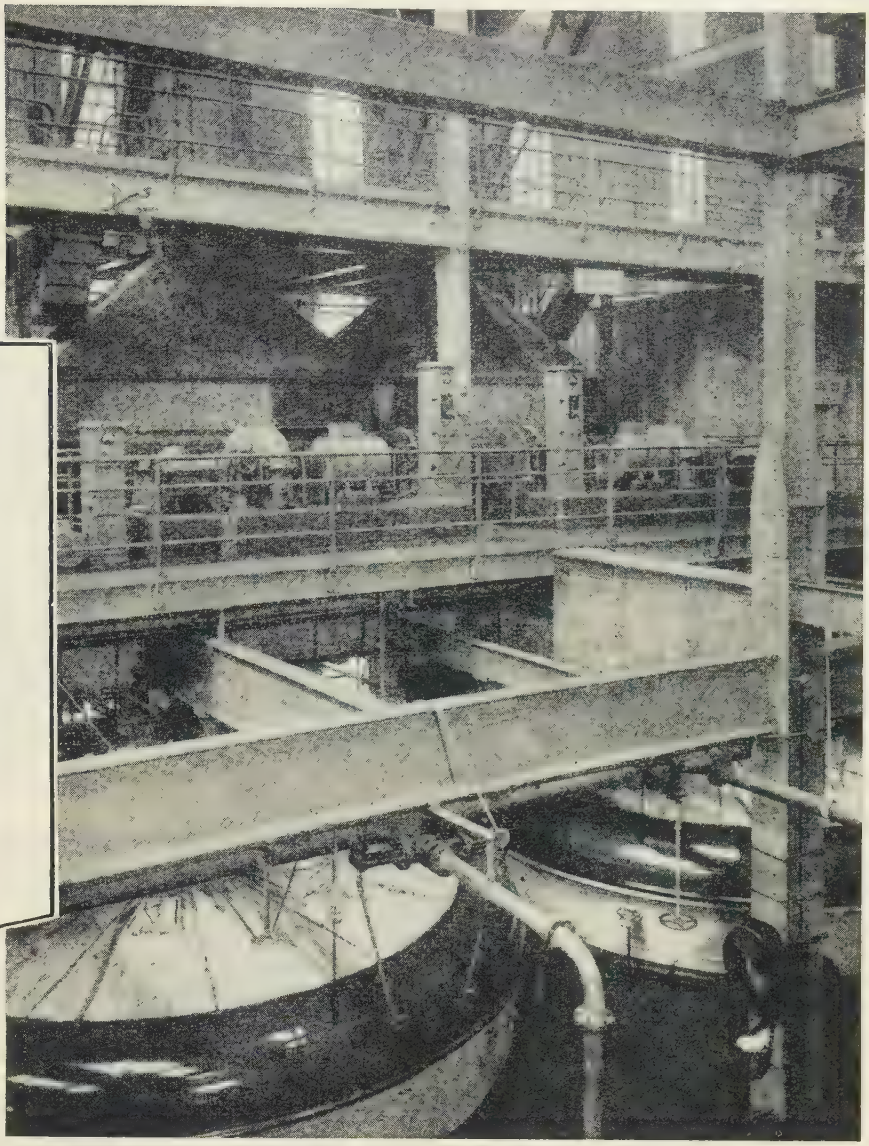

Installed at Guinness's Park Royal Brewery

Brookhirst Control Gear was supplied to Arthur Guinness Son & Co. Ltd., for controlling the processing plant in their Park Royal Brewery. In the illustration are shown three motor starting panels for drives situated in the Brew House.

As specialists with over fifty years' experience, Brookhirst are almost invariably associated with notable installations. They are called upon to solve motor control problems in activities as diverse as the manufacture of household goods and the production of atomic energy. With a world-wide reputation for quality, reliability and service, Brookhirst control gear is the inevitable choice of all who specify the best as a matter of long-term economy.

The services of Brookhirst Specialist Engineers are available to all concerned with the ordering, supplying and installing of control gear.

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BROOK GRYPHON FRACTIONAL HORSE POWER MOTORS

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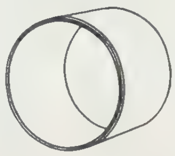
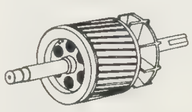


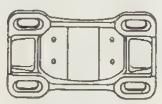
3/16" rolled steel shell makes a stout outer frame.

ROTOR



Pressure cast aluminium rotor, dynamically balanced to give vibration free running.

FEET



Accurately machined cast iron feet. Firmly fixed but easily detachable.

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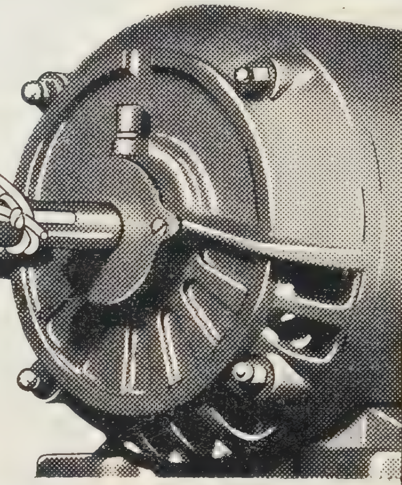

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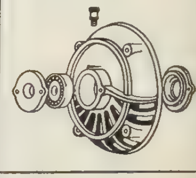
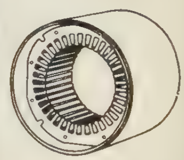


Super silent ball bearings fitted as standard.

STAMPINGS



Pressure assembled pack ensures a rigid stator winding.

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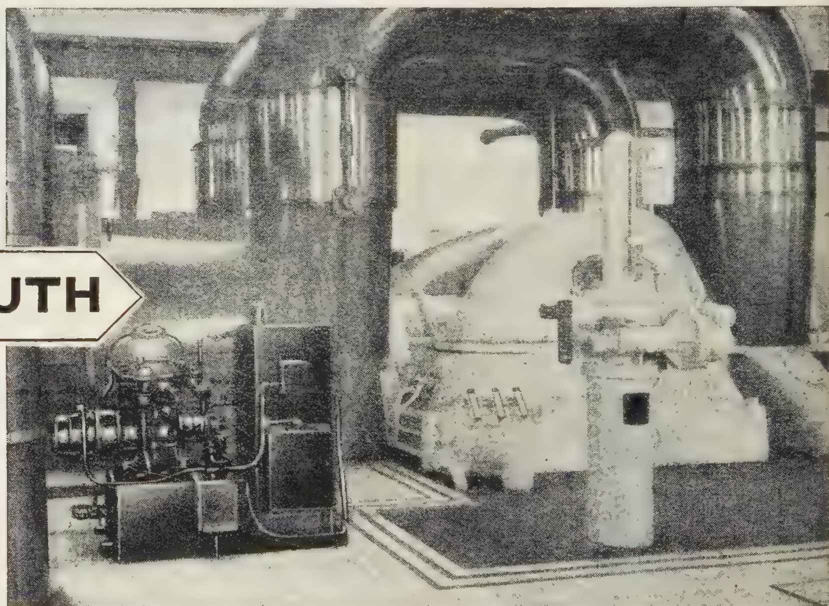

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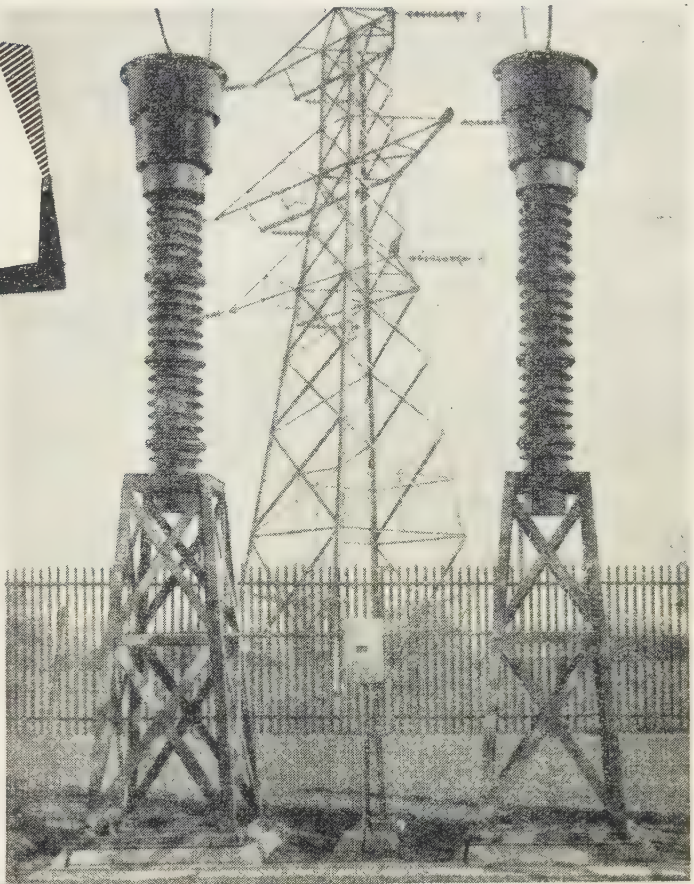

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Connection between station carrier equipment and the power lines is effected by G.E.C. Broad-Band Coupling Equipment.

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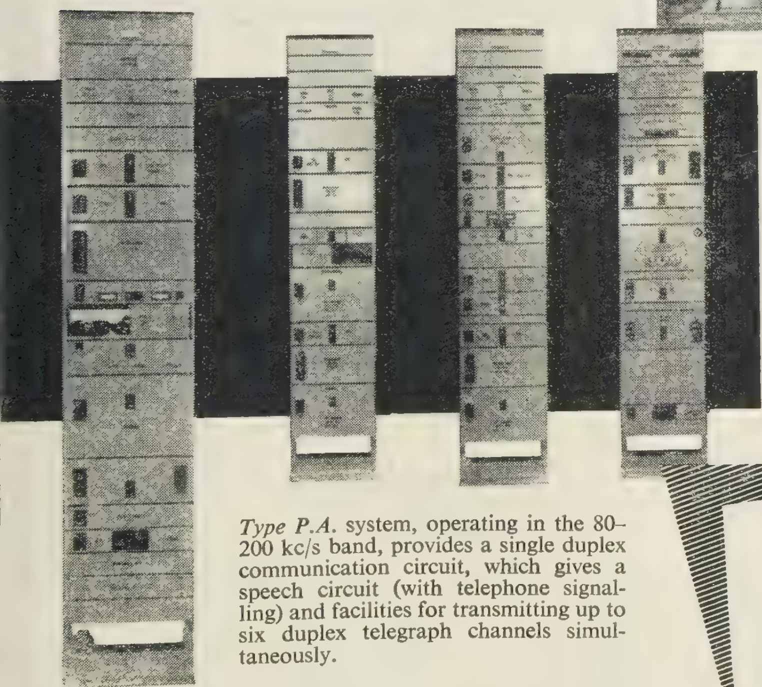

Type N system, operating in the frequency band 90–480 kc/s, provides up to eight duplex circuits over one route. Each of the eight gives a speech circuit (with telephone signalling), with facilities for transmitting up to six duplex telegraph channels simultaneously.

Type P.A. system, operating in the 80–200 kc/s band, provides a single duplex communication circuit, which gives a speech circuit (with telephone signalling) and facilities for transmitting up to six duplex telegraph channels simultaneously.

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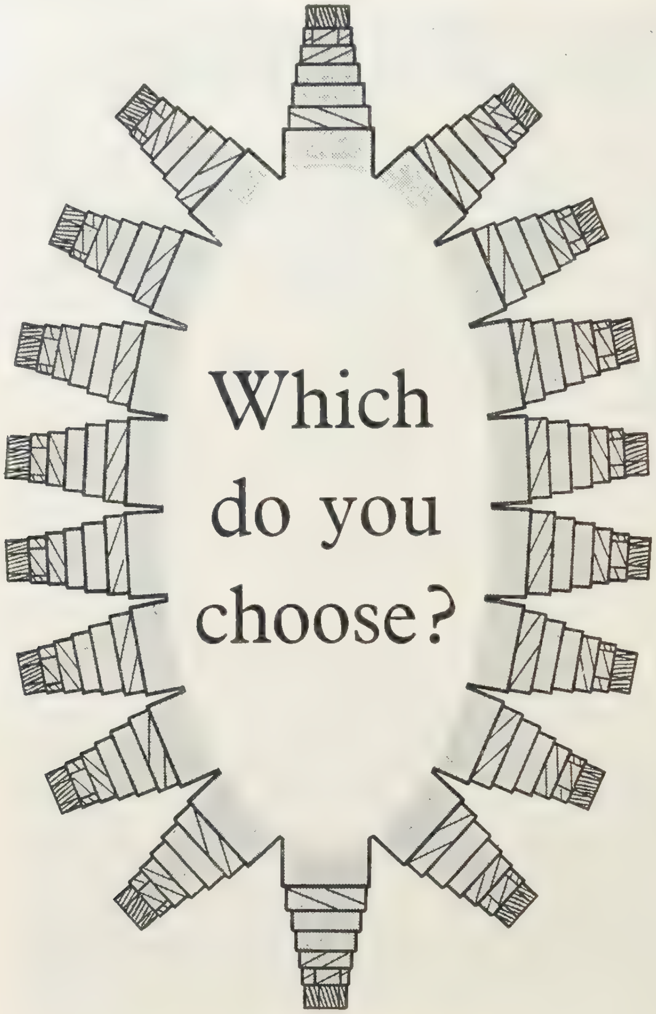

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There is one safe course . . . use the cables which are not only made to specification but have had equal attention given to the *unspecified* details — in other words, choose . . .

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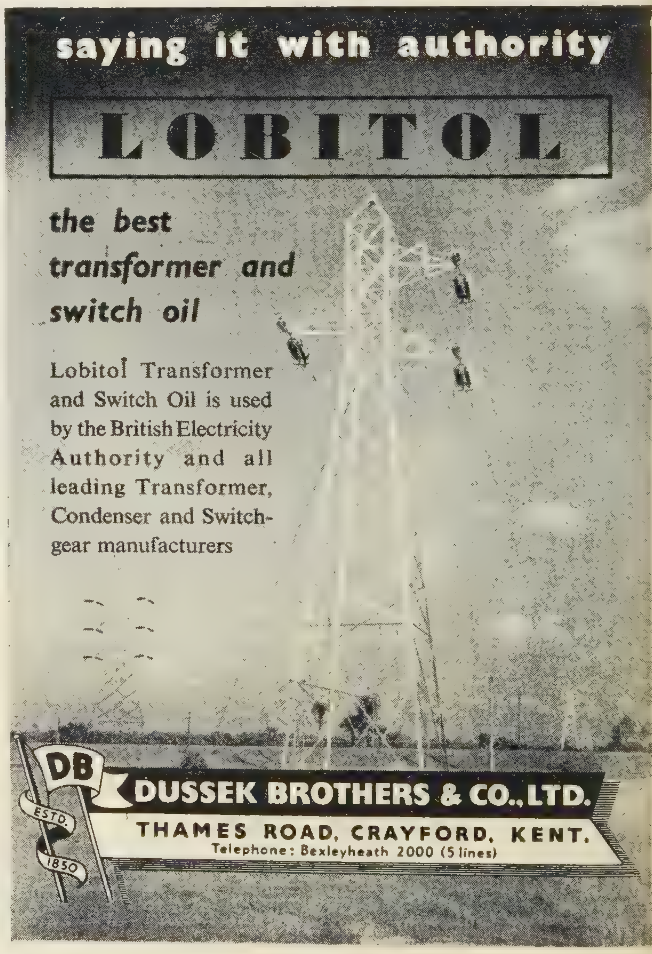
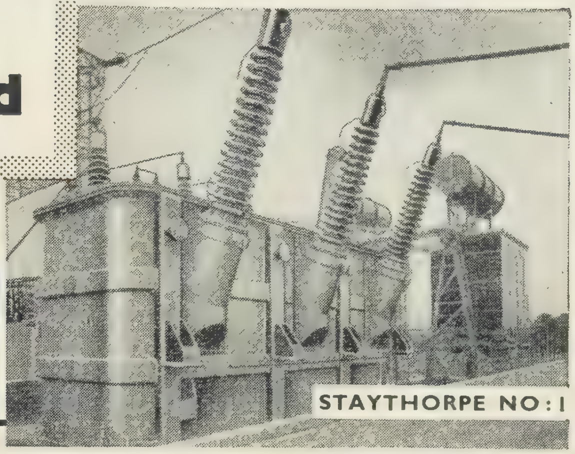


120 MVA TRANSFORMERS
for the
275 kV
British Supergrid

IN SERVICE

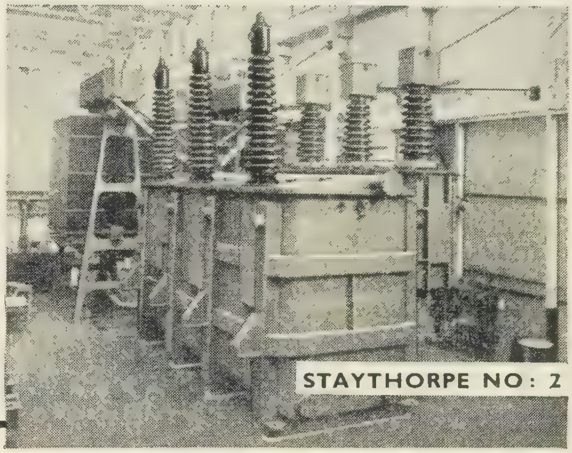
The first of ten BTH transformers for the BEA supergrid was transported to site early in 1953, and was officially commissioned in July of that year.



READY FOR SERVICE

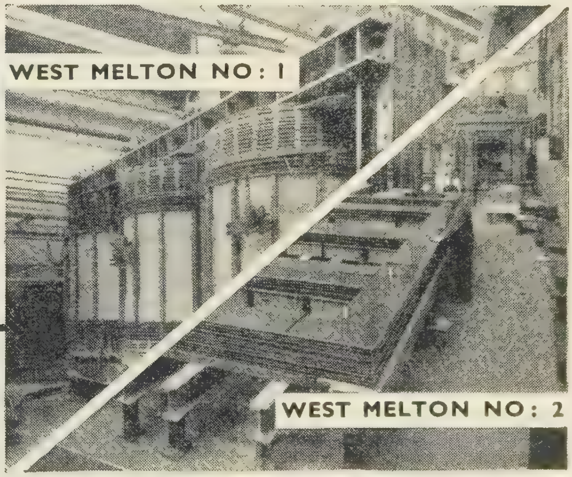
This transformer is now on site, having passed satisfactorily all specified tests including:—

Heat run at full-load losses.
Induced voltage tests at 460 kV to earth and 550 kV between phases.
Impulse tests on 275 kV windings at 1050 kV.
Impulse tests on 132 kV windings at 550 kV.



IN PRODUCTION

The two transformers for West Melton Substation are now under construction at Rugby. No. 1 has its core and windings assembled, while the core of No. 2 has been laid down.



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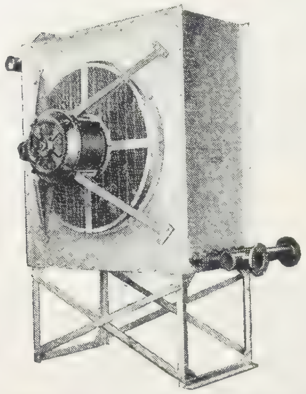

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Water cooled Cooling Coil for Transformer.

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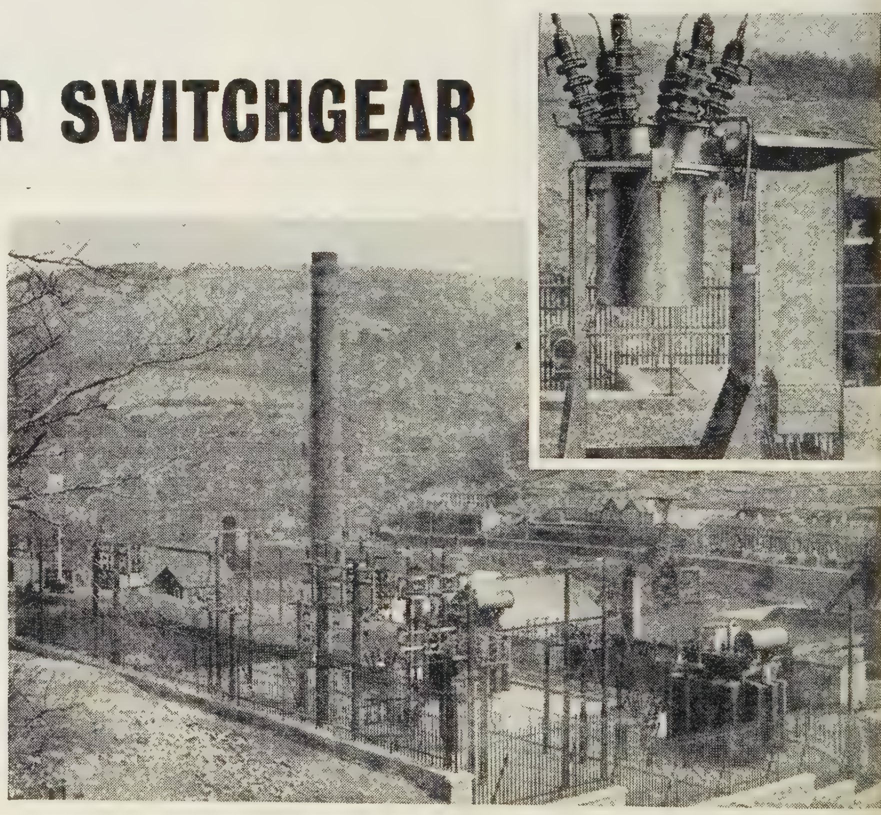
33kV OUTDOOR SWITCHGEAR



A Monmouthshire colliery sub-station equipped with S.W.S. 33,000-volt, 500-M.V.A. outdoor oil circuit breakers.

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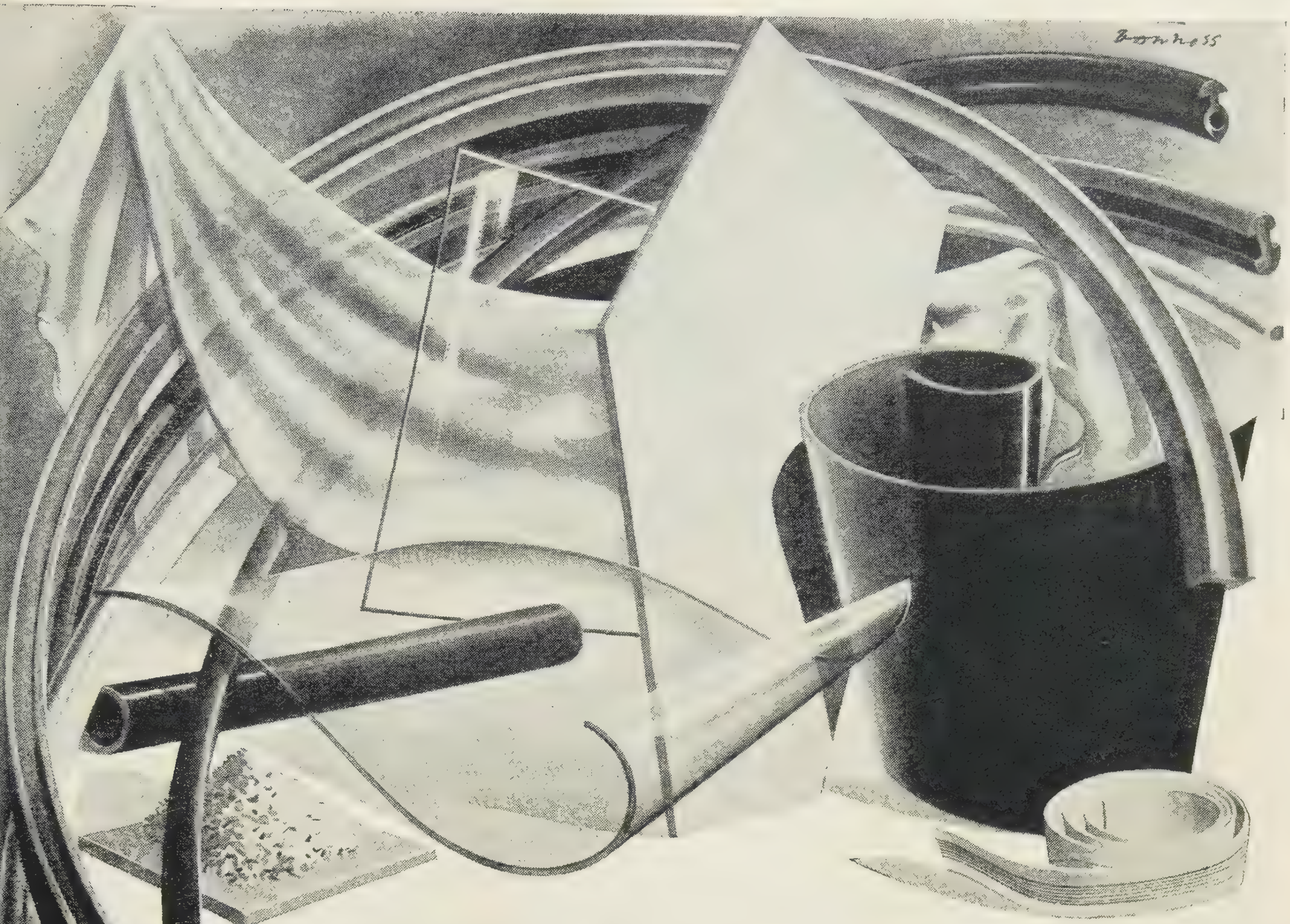

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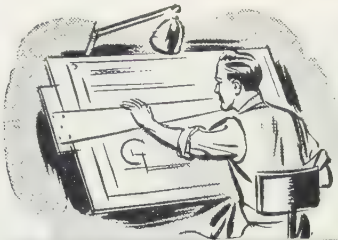

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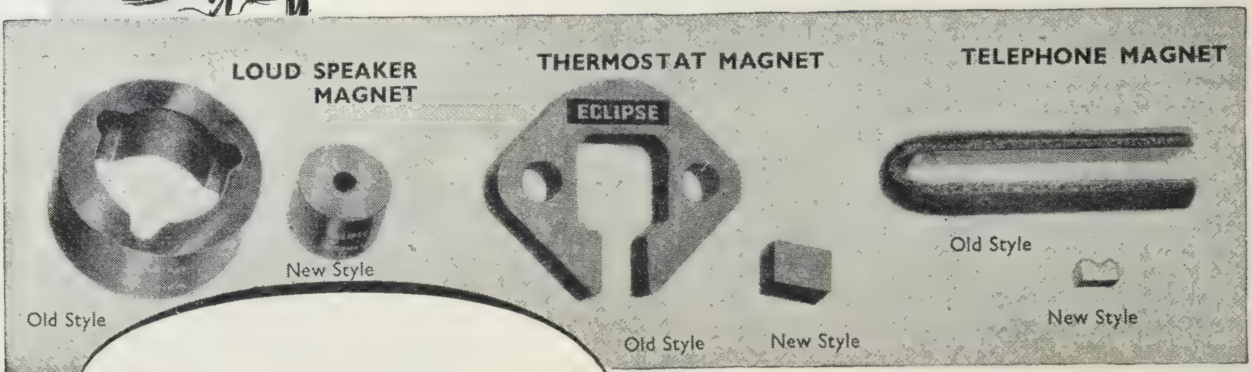

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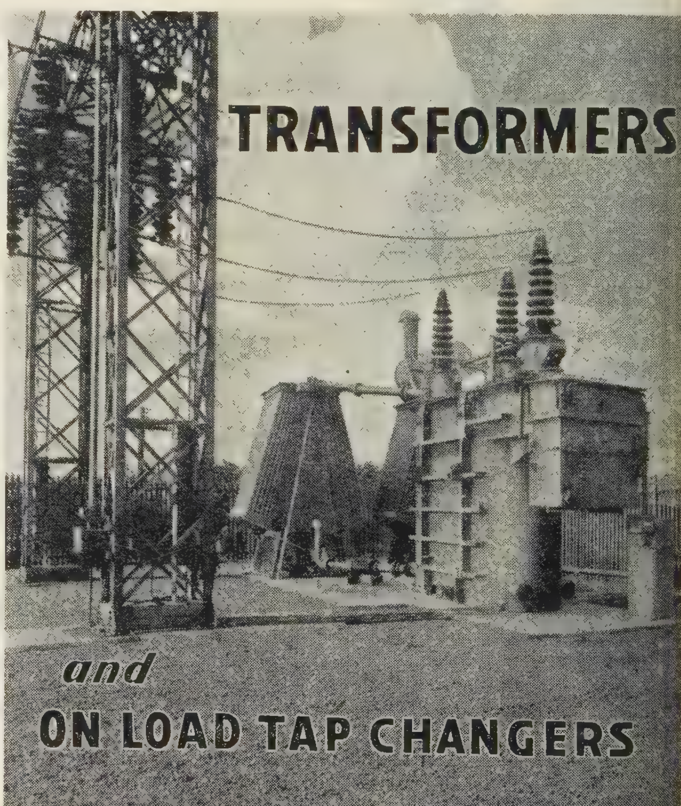

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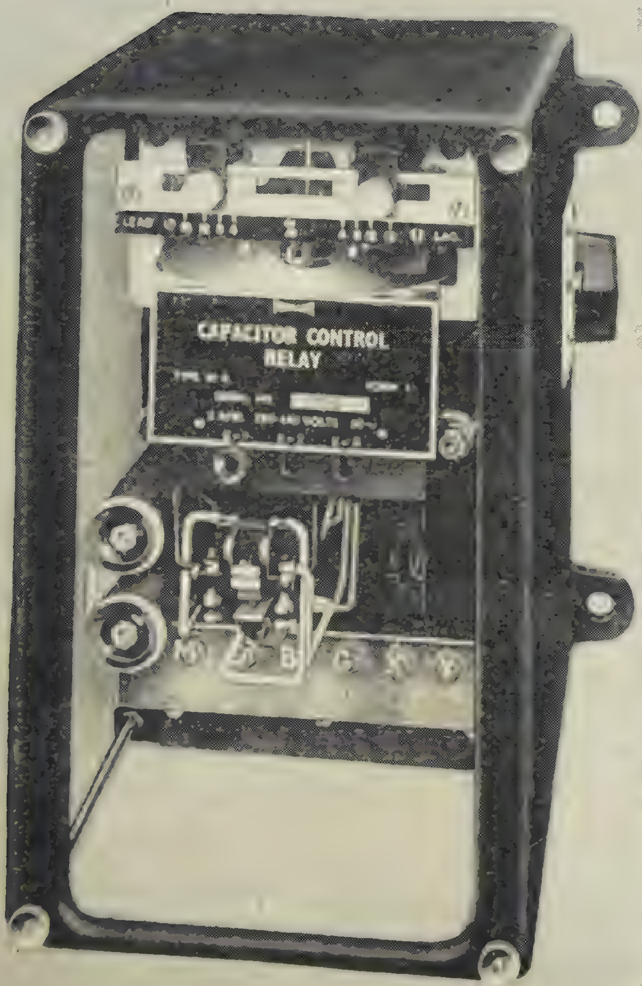
(TYPE WR)

FOR SINGLE STAGE CONTROL



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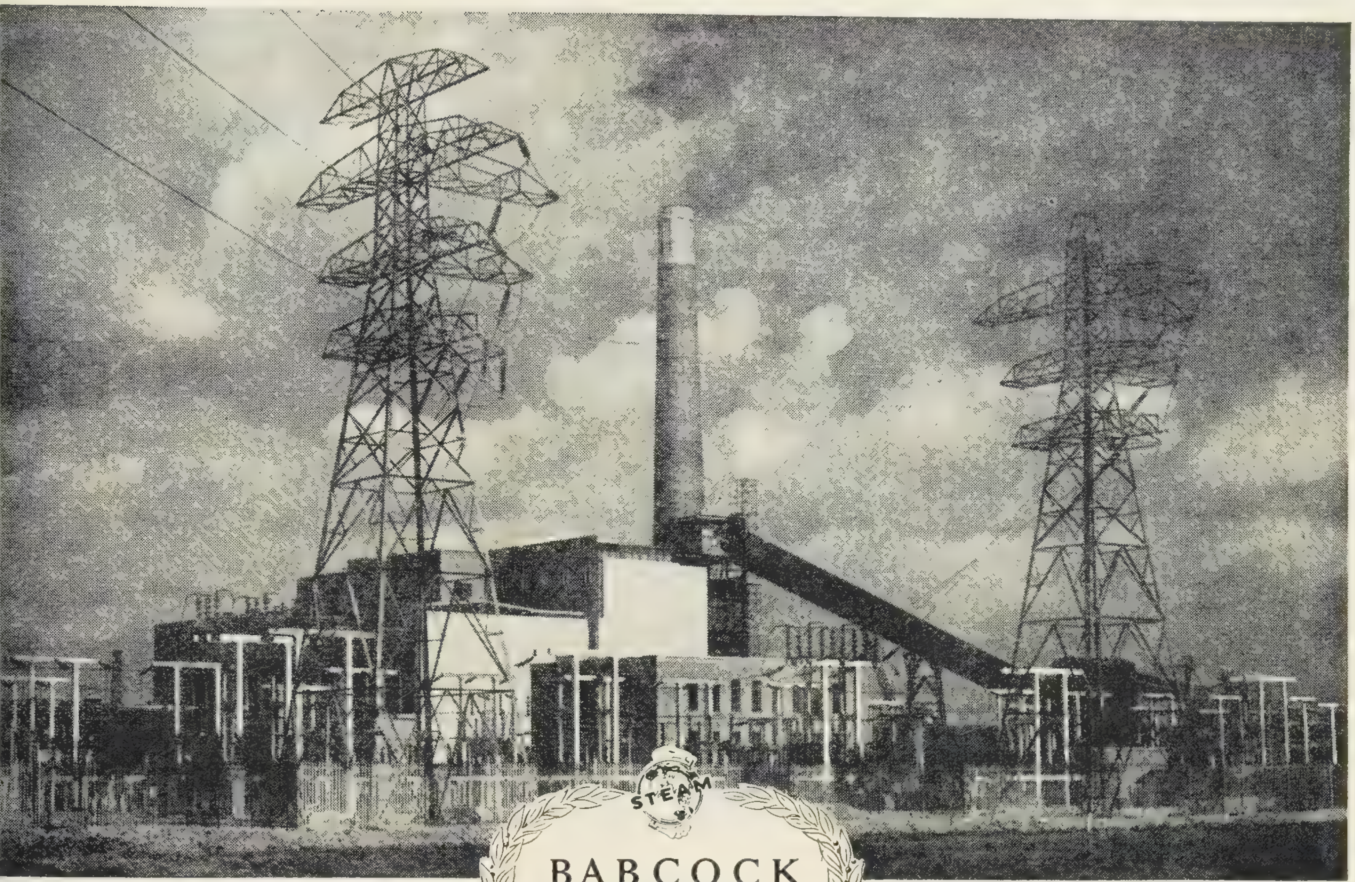

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B.E.A. NORTH WESTERN DIVISION

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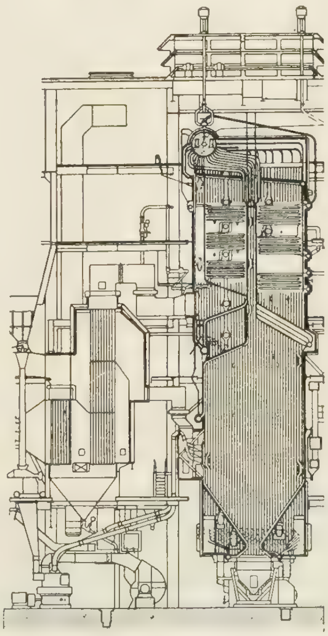
The contract includes all the coal pulverizing plant, comprising 28 Babcock type E mills to feed seven boilers.



Ash, collected in the 'A' type water-filled hoppers is discharged to sump by the "*Hydrojet*" system, being pumped to settling ponds by "*Hydroseal*" ash pumps. Dust is extracted from the precipitator and air-heater hoppers by the "*Hydrovac*" system. All this is Babcock equipment, widely used in both power station and industrial installations.

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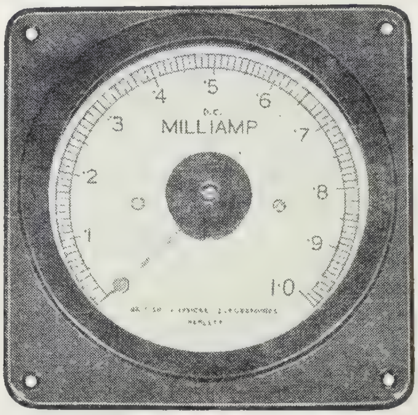

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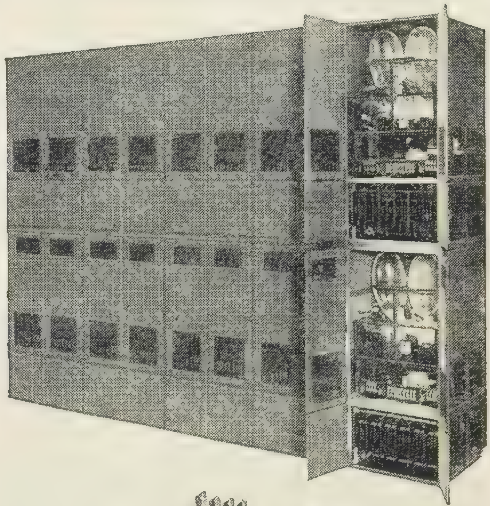

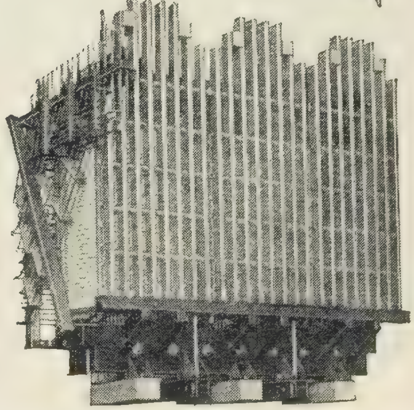

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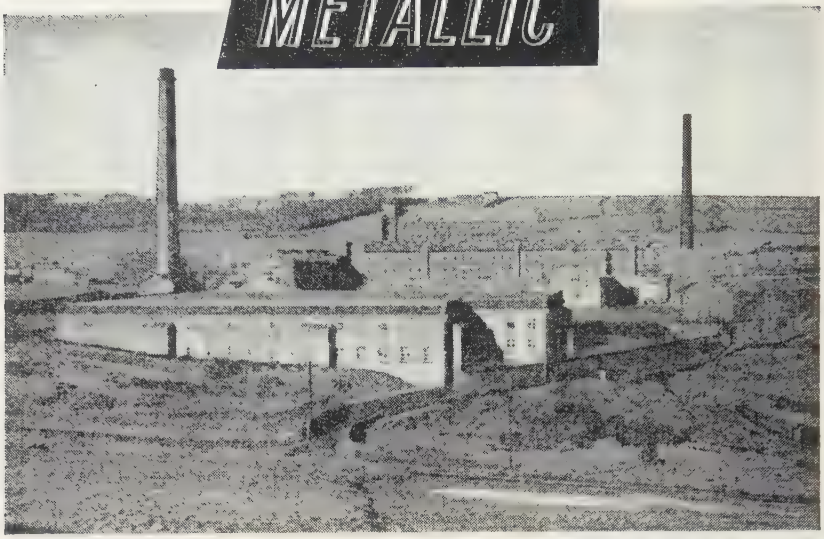

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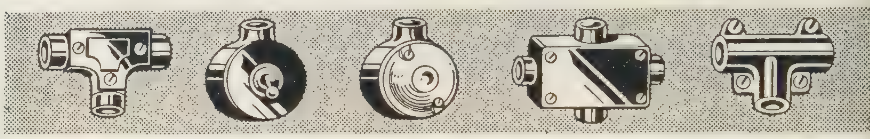

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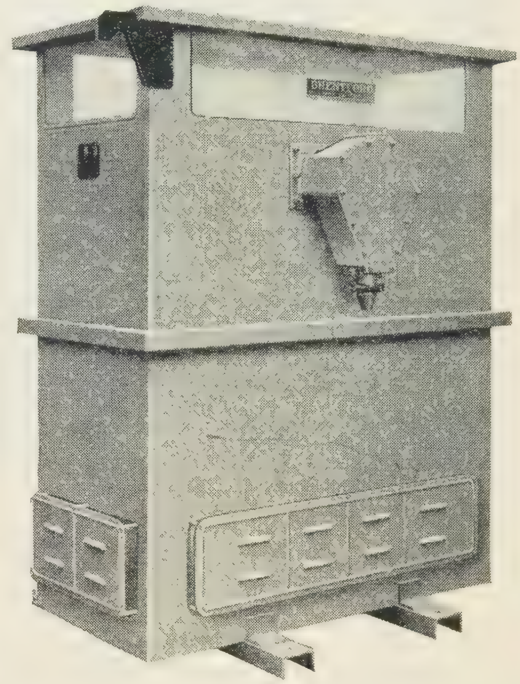

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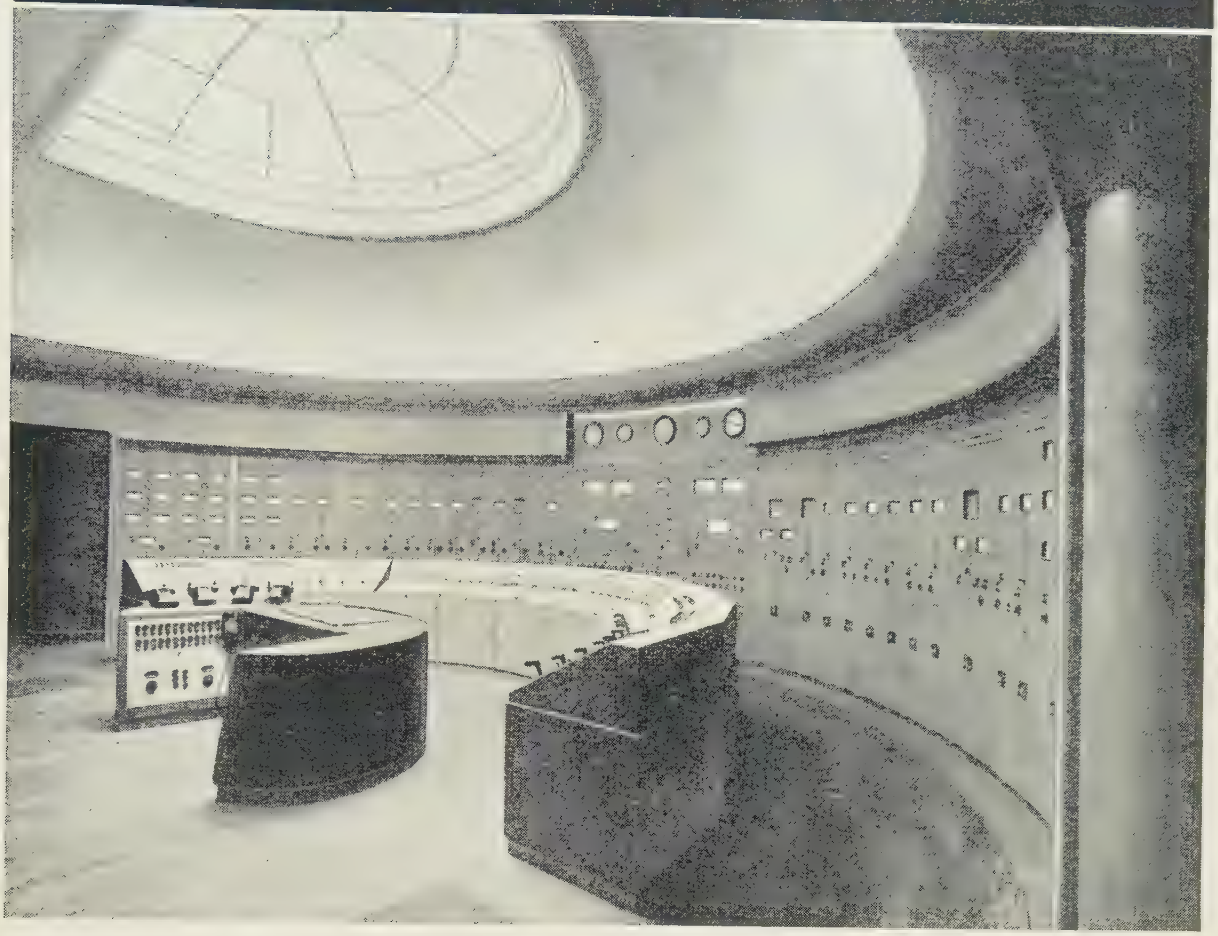

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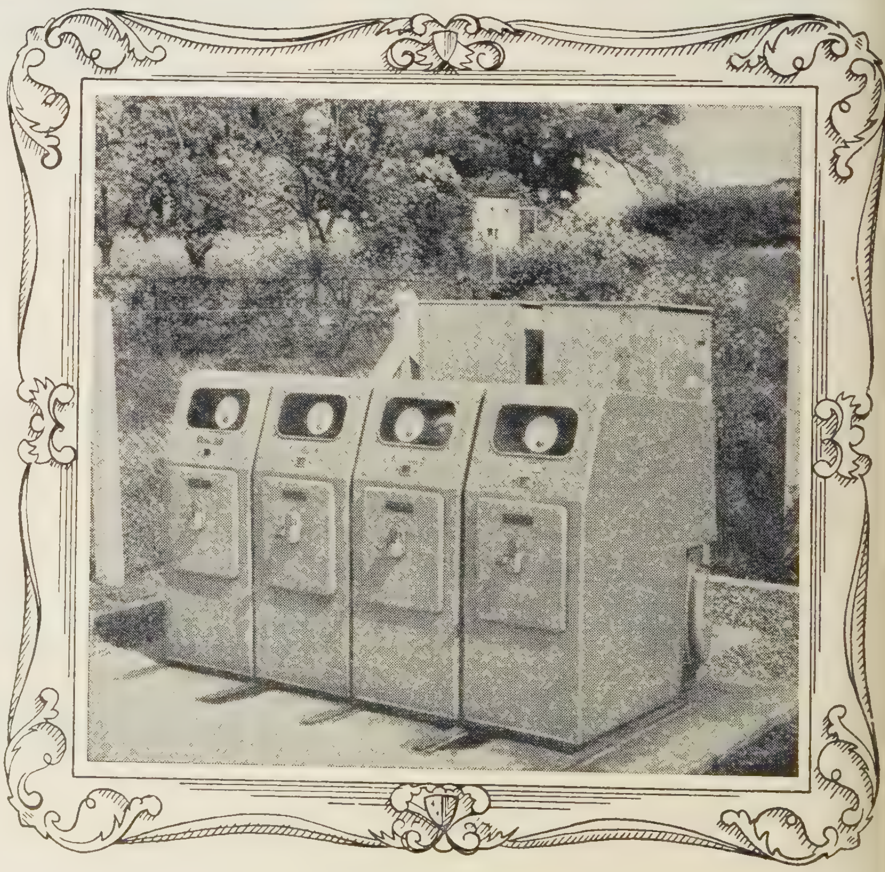

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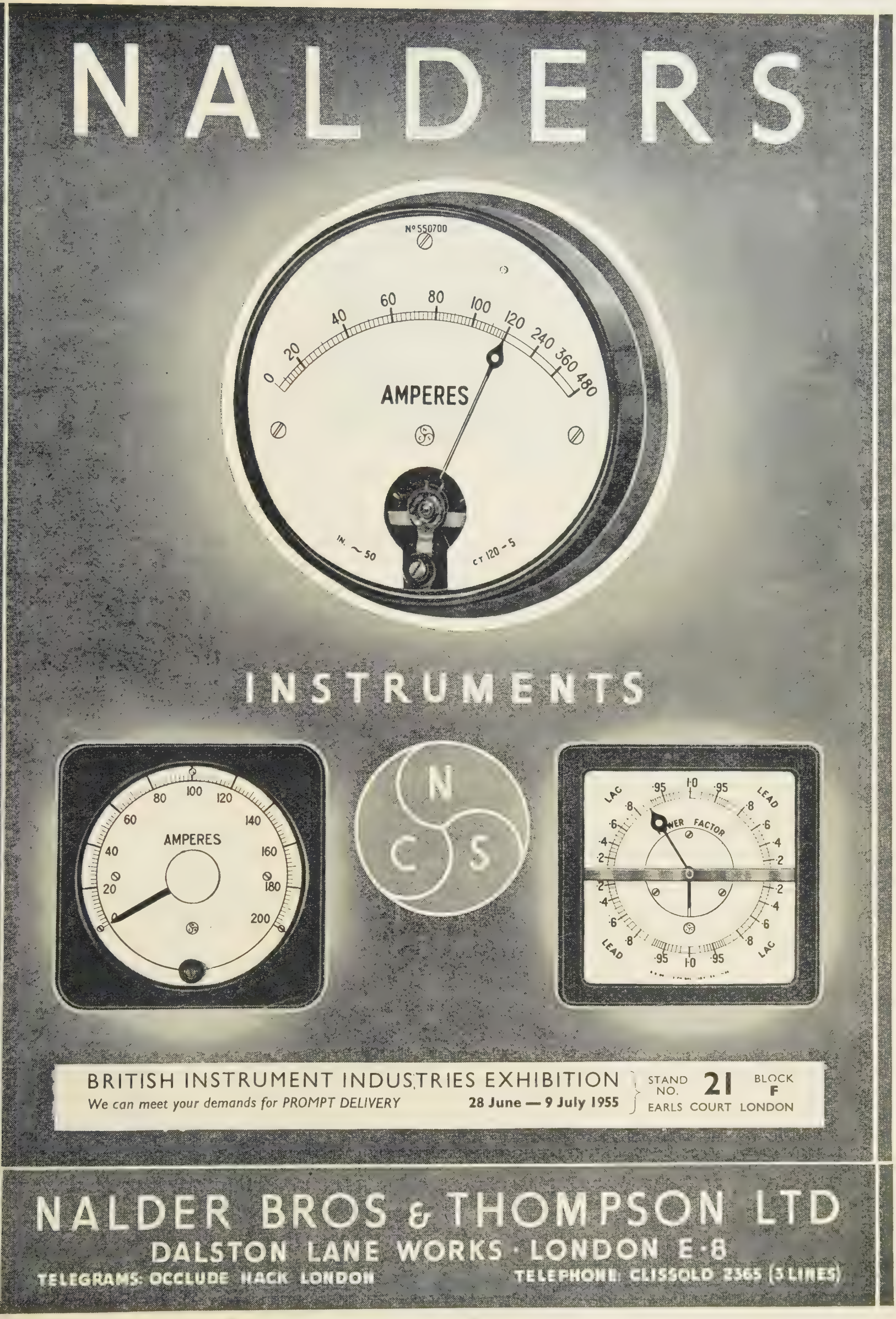
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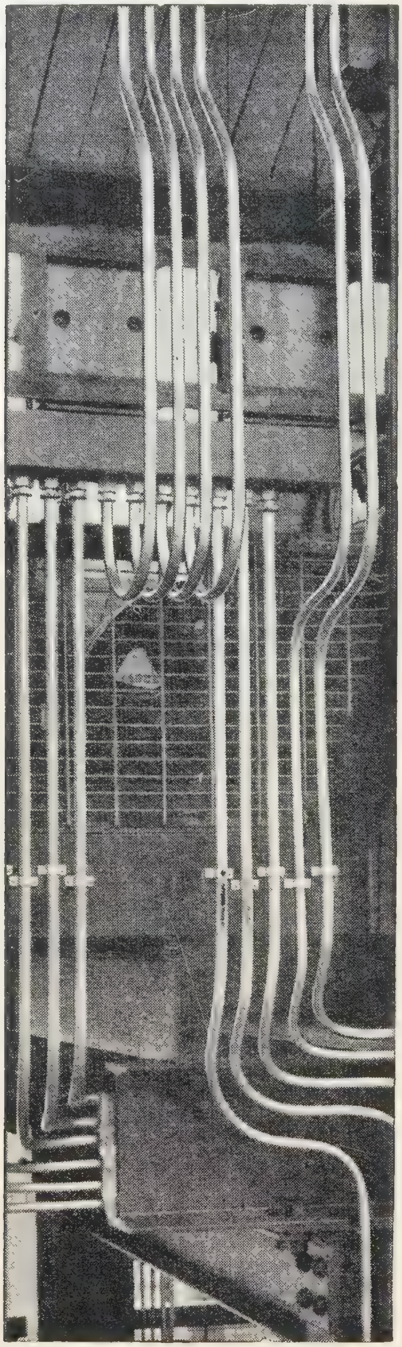

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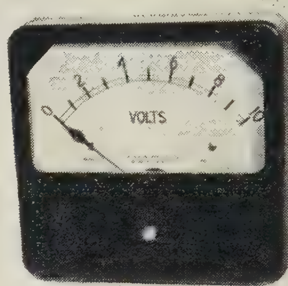

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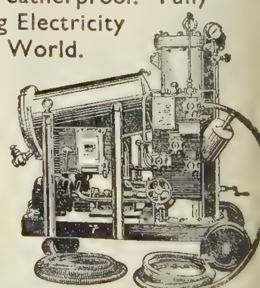

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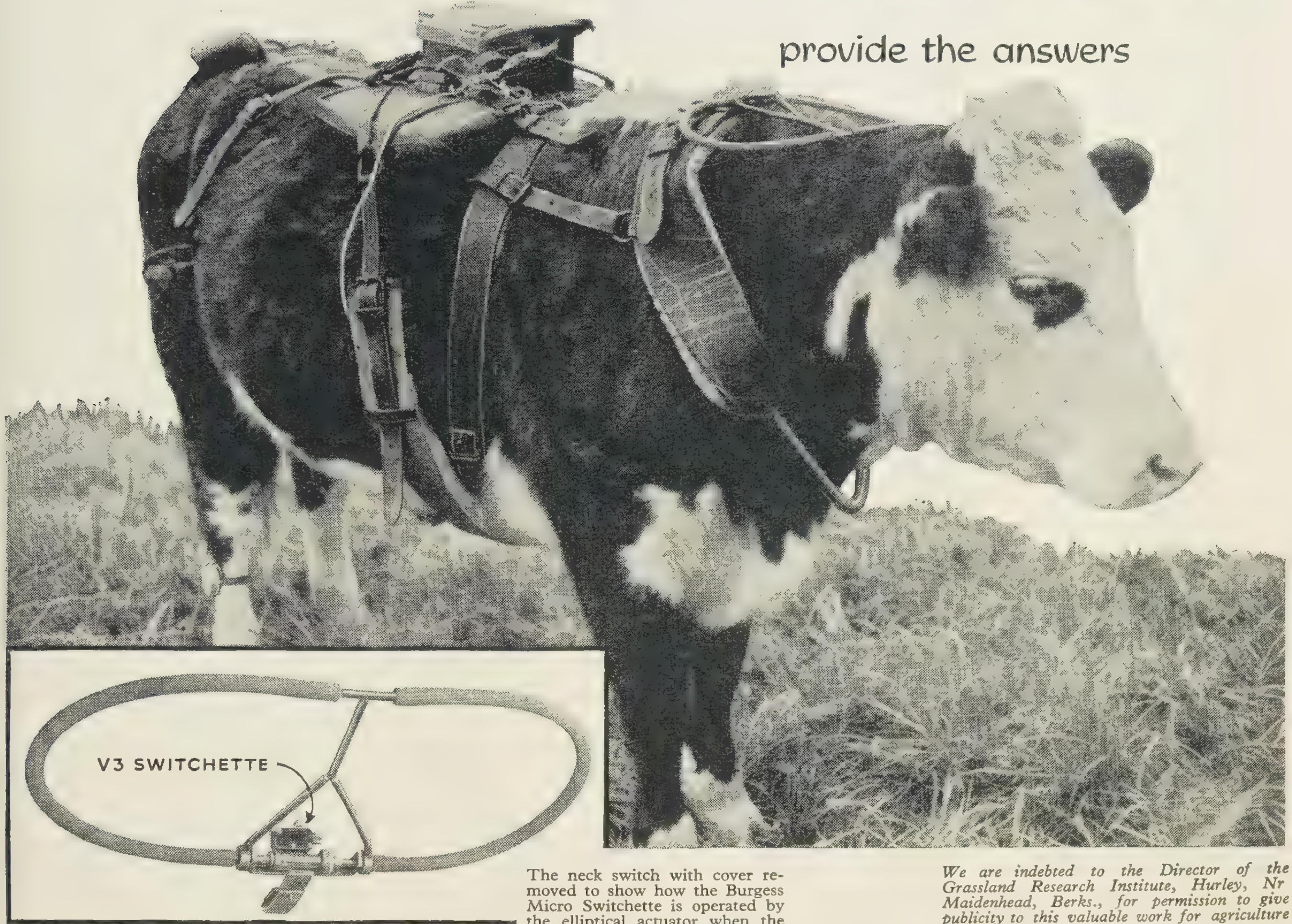

The neck switch with cover removed to show how the Burgess Micro Switchette is operated by the elliptical actuator when the head is bent forwards.

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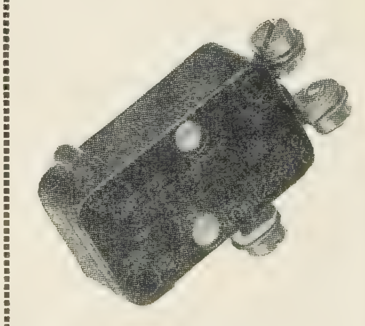

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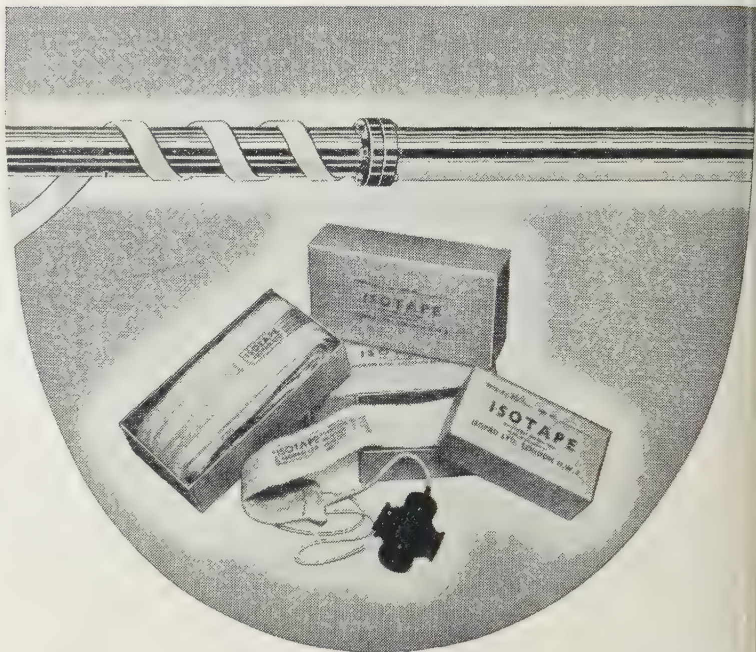

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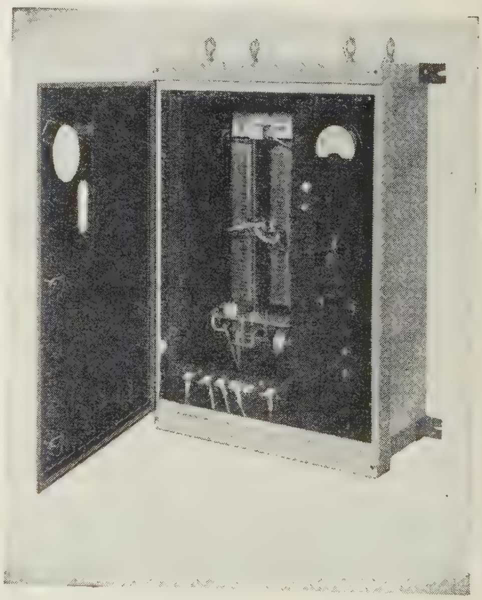

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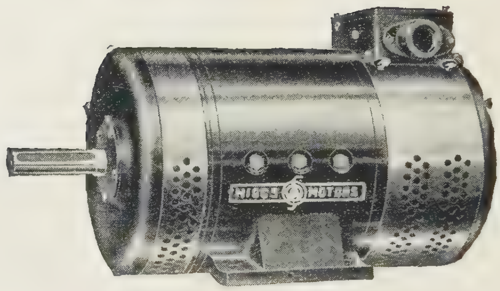

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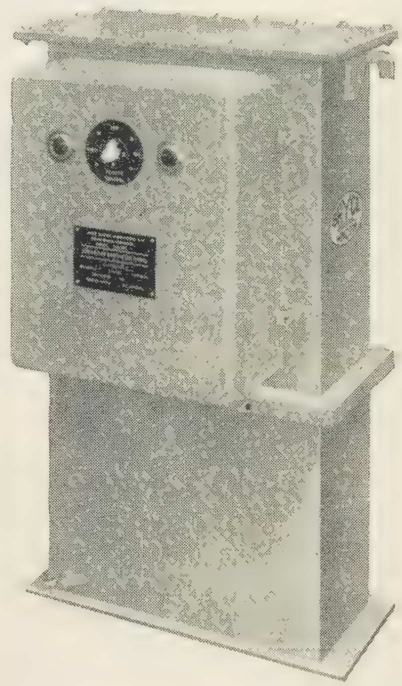

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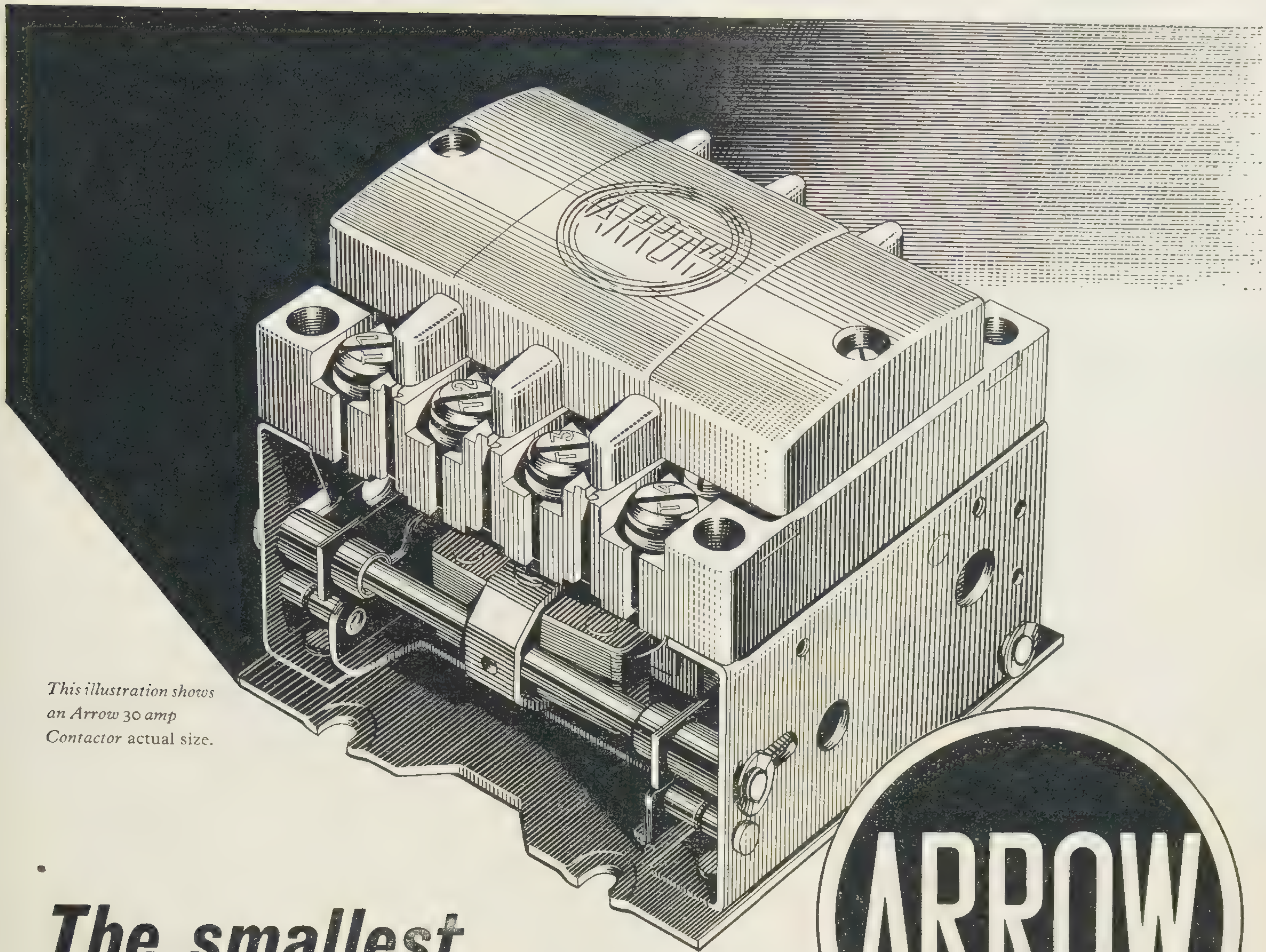

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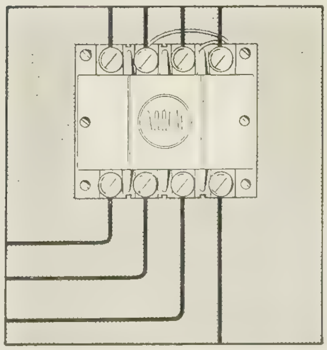

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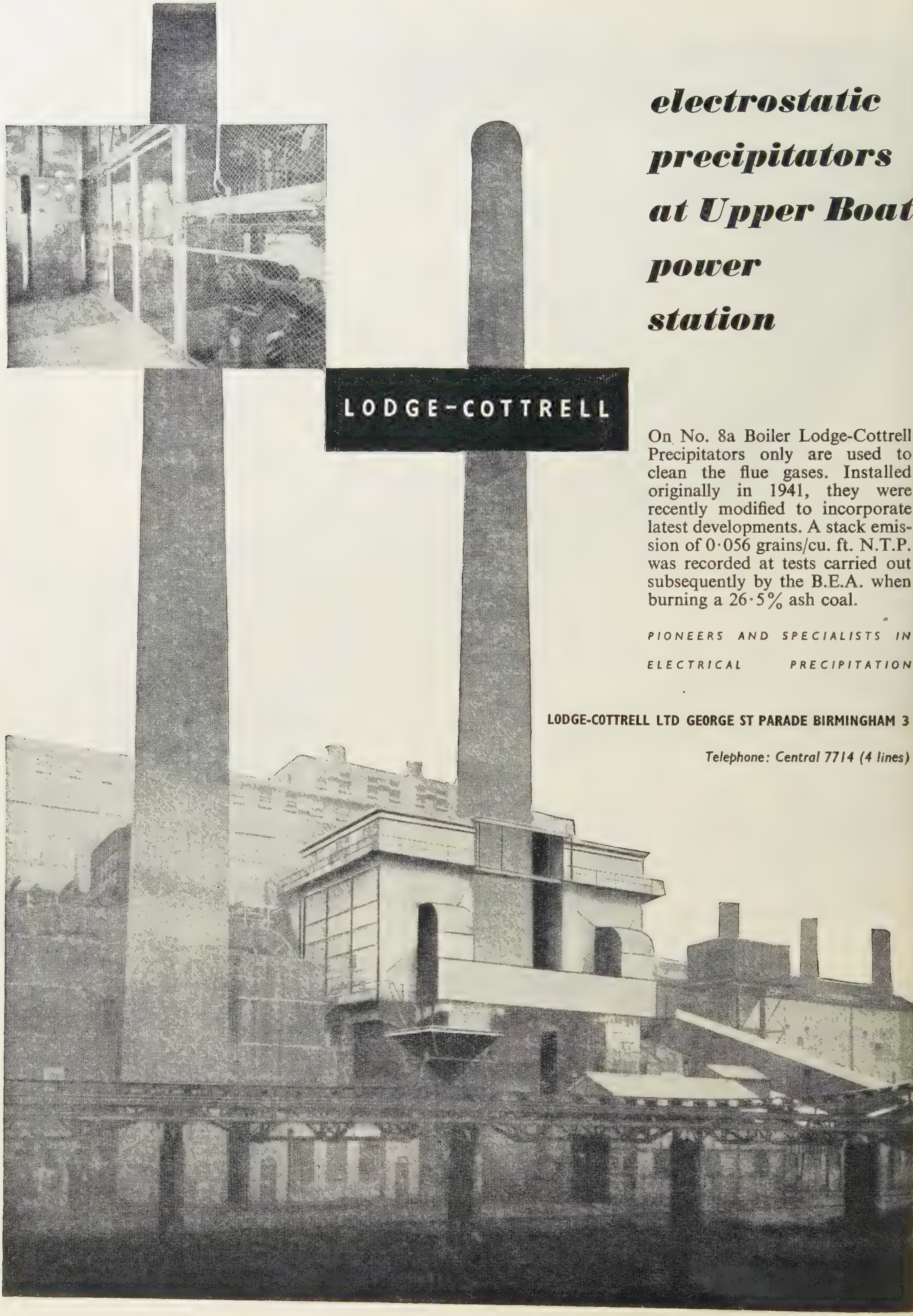
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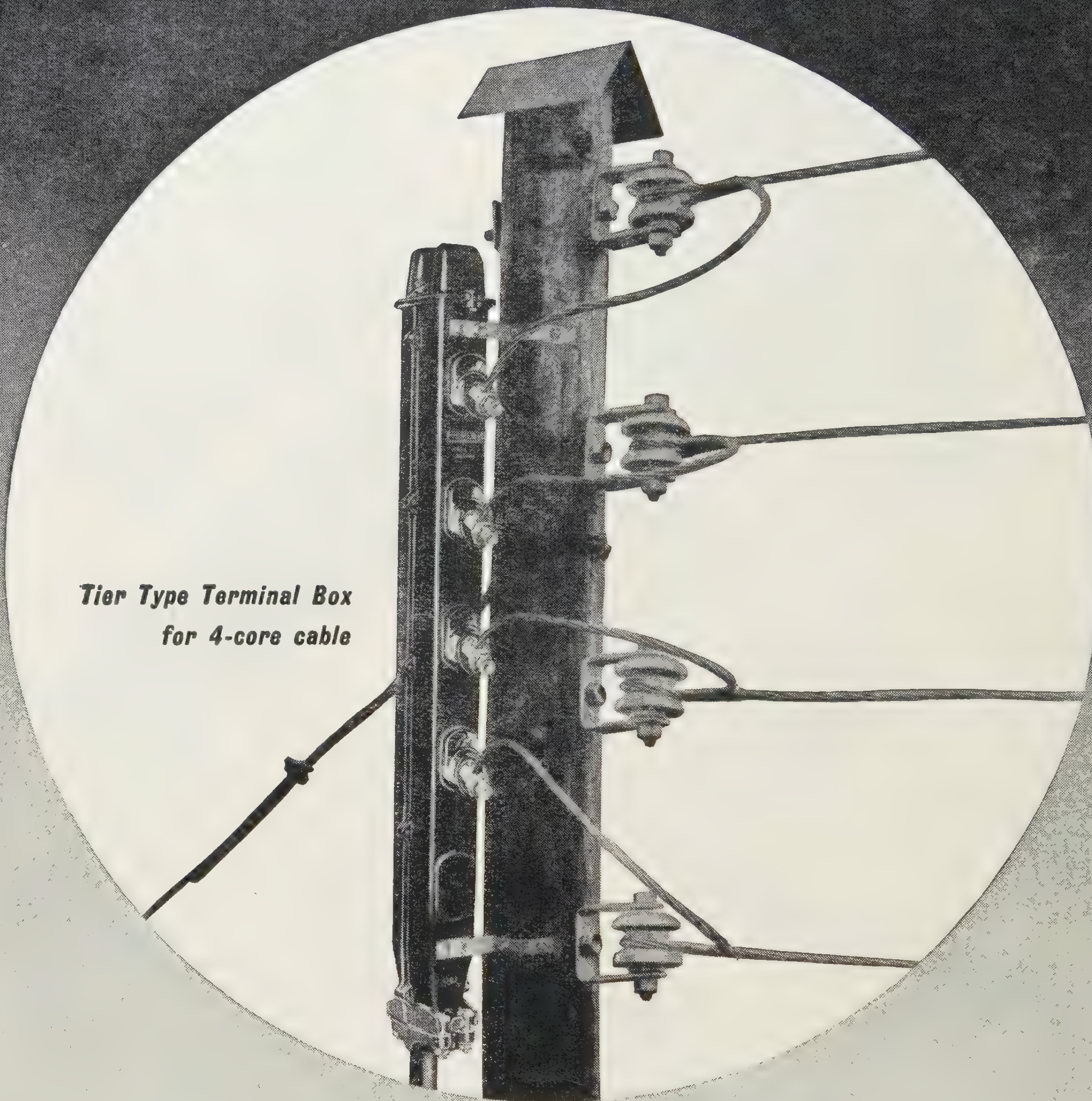

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VOL. 102. PART A. No. 2. APRIL 1955

621.313.322–81 Paper No. 1683 S
July 1954

SHORT-CIRCUIT FORCES ON TURBO-ALTERNATOR END-WINDINGS

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(*The paper was first received* 31*st October*, 1953, *and in revised form* 24*th March*, 1954. *It was published in July*, 1954, *and was read before the* NORTH STAFFORDSHIRE SUB-CENTRE 22*nd November*, *the* NORTH-EASTERN CENTRE 13*th December*, *and the* SUPPLY SECTION 15*th December*, 1954, *and the* SOUTH MIDLAND CENTRE 7*th March*, 1955.)

SUMMARY

A brief review is given of some factors relevant to short-circuit testing of alternators. The forces acting upon the stator conductors, particularly outside the slot, are described and the difficulty of analytical assessment of the damage to insulation is pointed out. Some details are given of the results of test short-circuits on a 60-MW turbo-alternator and also of tests on an experimental replica stator. The degree of correspondence between the short-circuit forces on an alternator and those on such a replica stator is considered in the light of tests carried out to establish this point. A discussion is given of various factors contributing to the severity of short-circuit forces which may occur in service and under present test conditions. The suggestion is advanced that a study of available data concerning actual operational faults be made with a view to obtaining agreement on a more realistic short-circuit test before machines are despatched.

(1) INTRODUCTION

The phenomenal advances in the output of individual turbo-alternators in recent years have presented the designer with increasingly difficult problems. Among these, although it is not insuperable, is the requirement of incorporating in the stator end-windings sufficient mechanical strength to withstand the forces which would occur if a solid short-circuit were applied at the generator terminals, at the same time providing adequate spacing between the coils for the passage of the cooling medium.

Thirty years ago a 20 000-kW generator was considered to be a large unit; generating voltages were low, the sets often being in close proximity to their loads. Many large industrial consumers of electricity, such as factories and collieries, installed their own generating plant, the output from which was fed into long runs of open busbars. Faults in these circumstances were not uncommon, and a busbar flashover represented a short-circuit electrically close to the machine terminals. It was probably in the light of this type of operation that clause 36 was included in the relevant British Standard (B.S. 225: 1925). This states that "Short-circuit tests, when required, shall be specified at the time of inviting tenders for the machine."

At that time it was reasonable to require an alternator to be subjected, on test, to a severe terminal short-circuit, since this was a likely operational contingency. Over a number of years the principle was thus established of applying 3-phase short-circuits from full voltage on those early and relatively small machines. These tests are not specifically required by B.S. 225, but the precedent having been set, manufacturers have felt bound to accede to continued requests for the application of full-voltage short-circuits on machines of ever-increasing ratings.

The development of high-voltage transmission led to the interconnection of existing power stations and to the construction of new stations satisfactorily placed with respect to fuel supply and cooling-water facilities. Generation may now be carried out at some distance from the load centres, and large alternators, more often than not, are solidly connected to individual step-up transformers with relatively short runs of busbars on the low-voltage side. The likelihood of a fault at or near the machine terminals in these circumstances is therefore remote compared with the conditions obtaining when B.S. 225 was originally prepared.

Faults may occur fairly frequently on that part of the system connected to the high-voltage side of a generator transformer, but in such cases the fault-power and current from the generator are limited by the transformer impedance in addition to that of the alternator itself. In a typical case the peak initial current to a high-voltage fault might be reduced to half the value associated with a solid short-circuit at the machine terminals. Additional factors, referred to in Section 6, reduce still further the currents to be expected in modern installations.

In what follows it is suggested that short-circuit tests from full voltage represent progressively more severe and less realistic conditions as the sizes of individual machines increase. The highest ratings of 2-pole alternators supplied for British power undertakings over the last 30 years are illustrated in Fig. 1. Alternators of more than 100 MW rating at 3 000 r.p.m. are now in the course of manufacture in this country and still larger units are being considered. Generators rated at 250 MW at 3 600 r.p.m. are at present under construction in the United States, and machines of similar capacity will undoubtedly be made before long for connection to the British Grid.

The primary object of the paper is to promote discussion of the view that while some short-circuit tests are probably desirable as a check on alternator reactances and on general manufacturing

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standards, it is unnecessarily severe to apply such tests from 100% rated voltage.

(2) SHORT-CIRCUIT FORCES

The particular aspect of alternator short-circuits with which the paper is mainly concerned is that relating to the forces acting upon the stator conductors, and especially those on the stator end-windings. As is well known, each one of a group of current-carrying conductors experiences electromagnetic forces whose magnitude and direction depend upon the configuration of the conductors and the amplitude and phase of the currents. The instantaneous force on any small element of conductor is given by

$$F = 0{\cdot}57IB \sin \theta ds \times 10^{-6} \text{ pounds} \quad . \quad . \quad (1)$$

where I = Current through the element, amp.
B = Magnetic flux density at that point, gauss.
θ = Angle between I and B.
and ds = Length of the element, in.

The direction of the force F is mutually perpendicular to the directions of I and B. If the circuits are in air B is directly proportional to the magnetizing force and therefore to the currents flowing in the configuration; the mechanical forces are then functions of current products.

(2.1) Forces on Stator Conductors

In a turbo-alternator having a subtransient reactance of 10% the initial current following a 3-phase short-circuit from no-load, rated voltage is ten times the full-load current. If maximum asymmetry occurs in one phase and decrement is neglected, a peak current will flow having a magnitude 20 times the peak value of full-load current. The peak forces associated with the conductors of that phase will therefore reach values of 400 times normal. The stator forces depend on many design features but in particular cases may increase more than proportionally with the output. The ratings of individual generators shown in Fig. 1

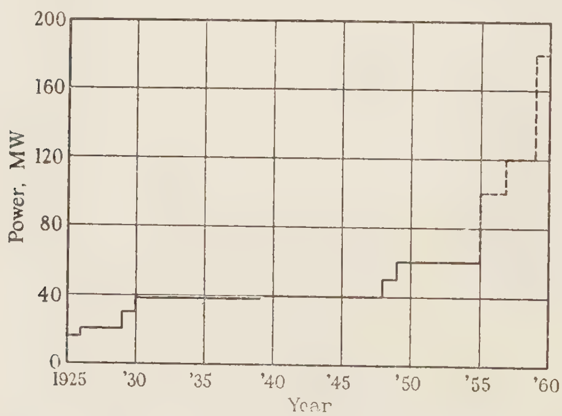

Fig. 1.—Ratings of 2-pole alternators installed on British electricity undertakings.

indicate that the short-circuit forces on the windings of present-day machines may be appreciably greater than those on the largest manufactured 30 years ago.

The presence of magnetic material in close proximity to the stator windings, particularly the rotor body and retaining rings, complicates the estimation of the forces; this point is discussed in Section 5.

The full-load forces on conductors embedded in the stator slots are not large, the torque being carried mainly by the stator iron. Where conductors in different phases occupy the san slot the repulsion forces between them must be restrained l the slot wedges; these can be designed to have sufficient streng for this duty under maximum-fault-current conditions, and litt difficulty therefore arises in the embedded portion of the stato winding due to the short-circuit forces. However, in the en winding structure which is in air, provision must be made t enable the conductors to withstand the possible displacing force Adequate bracing and packing must be provided without undu impairing the ventilation requirements of the machine.

The resultant force on any coil is that due to its own electro magnetically produced forces combined with those transferre mechanically from its neighbours through the packing block and binding; the length of the overhang is therefore an importa parameter in determining the total moment on the coil abo the core-end, where it may be regarded as being rigidly su ported. Modern alternators with high ratings require larg diameter stator bores with correspondingly longer overhang than those needed on smaller machines. This factor, in additio to the higher current values, must be considered in the desig of the bracing to restrain the short-circuit forces associated wi large generators.

(2.2) Analytical Expressions for Forces

For illustration purposes, consider the two layers of a stato end-winding to be developed into two parallel planes as show in Fig. 2. The point P is located on the outer conductor of th

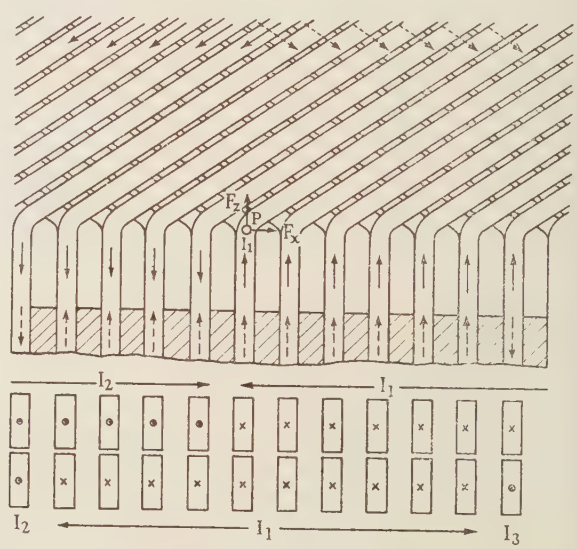

Fig. 2.—Simplified configuration of two layers of end-winding.

phase-1 band in the upper layer of winding; the sense of th currents in the various conductors is indicated by the arrows The diagram is considered to represent the xz-plane with th co-ordinate directions as shown by the forces at P. Throughou the cycle there will be a component of force at P, towards th remaining conductors in the phase-1 group, which will var as I_1^2. Owing to the adjacent phase-2 coils there will be a forc proportional to I_1I_2, whose direction and magnitude will var over the cycle. Similarly, there will be components due to th conductors of phase-3 and due to the phase bands in the lowe layer of the winding. In general, the electromagnetic force a any point on a coil carrying current I_1 is given by

$$F_1 = k_{11}I_1^2 + k_{12}I_1I_2 + k_{13}I_1I_3 \quad . \quad . \quad . \quad . \quad (2$$

The coefficients k depend upon which conductor is under consideration and the position of the point on the conductor, while the instantaneous values of the phase currents I_1, I_2 and I_3 depend on the short-circuit conditions, i.e. the type of fault and the instant in the cycle at which it occurs. Some investigations on the effect of various types of short-circuit are given in Section 6.

Previously published analyses of end-winding forces appear to have been confined to approximations with regard to the shape of the coils. Calvert[1] and Zingales[6] consider a group of infinitely-long parallel equally-spaced co-planar conductors and give the expression for the force on the outer conductor of the group. Harrington[2] analyses a configuration similar to that shown in Fig. 2, the two layers of a conical end-winding being considered to be developed into parallel planes with the conductors represented by straight lines; values of the coefficients k are derived for the component of tangential force in the plane. This treatment is said to be reasonably accurate for a 4-pole alternator whose end-windings lie on cones having half-angles not greater than 25°. Harrington gives results of an investigation made to determine the effect of the stator iron on the magnetic fields in the end-winding, and the conclusion is reached that this is of minor importance over most of the coil length but has some effect on the portion of end-winding nearest to the coil knuckles.

An analysis has been made of the end-winding forces in a particular 2-pole machine for which it was felt that the treatment described in Reference 2 would not be sufficiently accurate. The correct 3-dimensional form of the windings has been considered by a method outlined in Appendix 10.1, and the coefficients k for the forces in the x, y and z directions are shown in Fig. 3 as functions of the length along the curved end-winding conductors.

It is evident that the total displacing force in any given direction will be represented by the area beneath the curves shown, and there will be, in addition, bending moments or couples acting upon the conductor which could also be evaluated from Fig. 3 together with information about the actual shape of the coil. In making any comparison between the figures given in Reference 2 and those shown in Fig. 3 it is necessary to recall that the former relate to a 4-pole machine and the latter to a 2-pole machine and also that F_x, F_y and F_z are the three components of the force at points on the true shape of the coils. In Reference 2 the coil is considered to comprise three sections and the total and average forces on each are given; no reference is made to the twisting couples mentioned above or to the effect of the rotor in modifying the forces under actual short-circuit conditions.

From the foregoing discussion it will be clear that the magnetic fields throughout the end-winding during short-circuit will have a somewhat complex distribution. Even if these are calculated and the forces computed, the resulting movement of the coils and the probable damage to the insulation would be almost impossible to evaluate. This is because it is difficult to ascribe quantitative values to the constraints afforded under dynamic conditions by the packing and binding. The problem is still further complicated if it is desired to make due allowance for any ageing in service of the insulating and supporting materials, and to take proper account of the operating temperature of the machine.

Analytical assessment of the damage likely to be produced in alternator windings as a result of a short-circuit therefore presents very considerable difficulties. It is desirable, however, from the viewpoints both of manufacturers and users of electrical plant, that any design should be proved to have sufficient mechanical strength to withstand whatever conditions it may reasonably be expected to encounter in service. It should be possible to establish specifically what can be considered to constitute a satisfactory demonstration of this requirement.

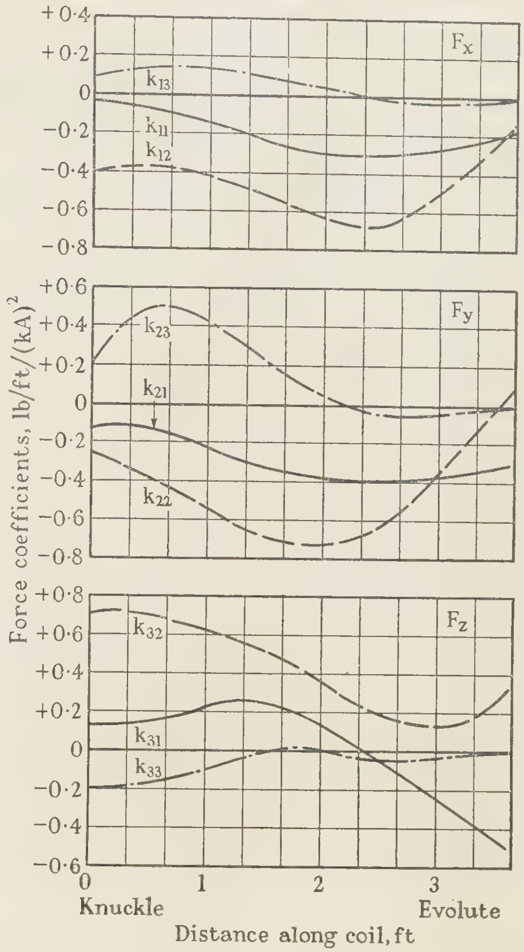

Fig. 3.—Calculated values of end-winding force coefficients for the outer conductor of a phase band on a 2-pole alternator.

$$F_x = k_{11}I_1^2 + k_{12}I_1I_2 + k_{13}I_1I_3$$
$$F_y = k_{21}I_1^2 + k_{22}I_1I_2 + k_{23}I_1I_3$$
$$F_z = k_{31}I_1^2 + k_{32}I_1I_2 + k_{33}I_1I_3$$

(3) INVESTIGATIONS INTO THE CONSEQUENCES OF A FULL-VOLTAGE SHORT-CIRCUIT TEST

The correlation of analytical work with practical experience was investigated with reference to a series of short-circuits under test conditions on the first of four 60-MW 3-phase 60-c/s 13·8-kV 3 600-r.p.m. alternators for a power station in Canada. The consultants handling the contract on behalf of the purchaser required the generator to be subjected to a solid 3-phase short-circuit from 100% of normal voltage on open-circuit.

(3.1) Short-Circuit Test Results

In order to check the correct operation of the oscillographic equipment associated with the test, two preliminary short-circuits were carried out, one at 50% and another at 75% of normal voltage, before the specified test from 100% voltage. Following these three short-circuits the alternator was run for several hours on open-circuit above normal voltage. The first indication that damage to the insulation had occurred was obtained when the windings failed to withstand for one minute the final high-voltage insulation test—namely twice the working voltage plus 1 kV, i.e. 28·6 kV. The windings had previously

withstood a test voltage of 30·6 kV between phases and to earth for one minute.

The results of the high-voltage tests were:

(*a*) The first phase failed on reaching 28·6 kV.

(*b*) The second phase failed at 21·0 kV.

(*c*) The third phase failed after withstanding 28·6 kV for 30 sec. These reduced values of breakdown were undoubtedly a direct result of the short-circuit tests.

On subsequent examination of the end-windings, a few loose ends of the binding material provided the only immediately obvious indication that some slight movement of the windings had taken place.

It is possible that had the operating voltage been 13·2 kV instead of 13·8 kV the windings of two phases might have withstood satisfactorily the corresponding test voltage of 27·4 kV for 1 min. In such circumstances the faulty top-half coil of the third phase would probably have been replaced and any loose binding renovated. Assuming that all three phases subsequently withstood the high-voltage test, the machine would, no doubt, have been accepted, and would have gone into service as healthy. This hypothetical case is mentioned only to emphasize the nature of the acceptance tests and to draw attention to their possible shortcomings. In the case of the machine referred to above, since three coil-sides required replacement it was decided to rewind completely and to obtain in the process as much information as possible regarding the extent of the damage to the insulation resulting from the short-circuit tests.

Measurements taken at the coil knuckles of the upper layer showed some permanent circumferential deflections, and a record was made of the displacement on each of the 60 half-coils in the upper layer; the average values obtained at the two ends of the stator are shown in Fig. 4. Each half-coil was then

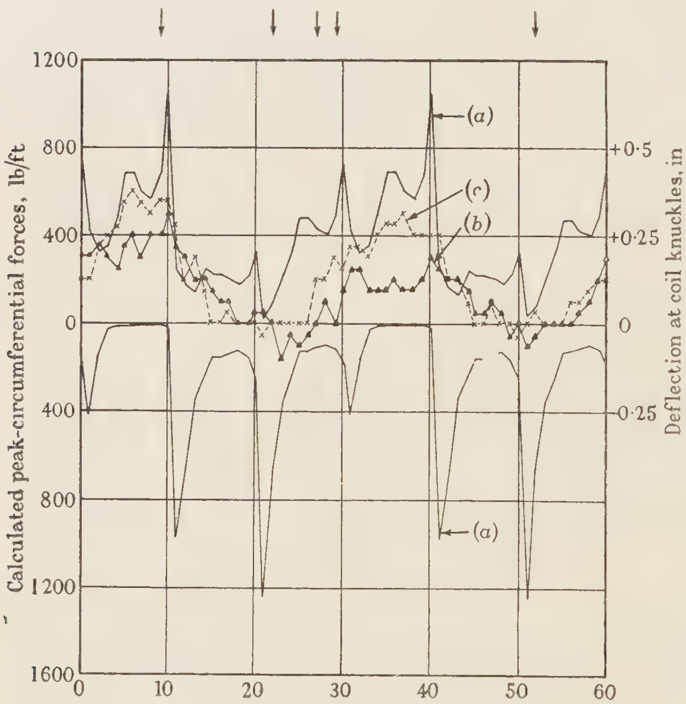

Fig. 4.—Results of short-circuit tests.

(*a–a*) Calculated envelope of peak forces at coil knuckles for a particular short-circuit from rated voltage.

Permanent circumferential deflections measured at coil knuckles on:

(*b*) Alternator.

(*c*) Replica stator similarly braced to alternator.

↓ Location in alternator of coils found to have reduced insulation strength following short-circuit test.

electrically isolated and high-voltage tested before removal fro its slot. Out of the total of 120 half-coils, 19 failed to witl stand voltages to which they had previously been successfull subjected. The location of 16 of these points of coil failu was just beyond the end of the core, clearly demonstrating th susceptibility of this portion of the insulation to damage b shock mechanical displacement of the end-winding structur One coil was found to have broken down in the slot and o two coils the point of failure was not recorded.

After the removal of the coils from the slots, the insulatio was examined at those points of breakdown which could b located. In all the 16 cases referred to, puncture was found t have occurred where the wall insulation had been strained owin to movement of the conductors. There was slight evidence c radial displacement at the coil knuckles, but the major cause c damage appeared to have been circumferentially-directed force From the subsequent analyses which have been carried out i appears that it is the latter component of the short-circuit forc which produces the greatest deterioration of insulation strengt in windings having a conical configuration. In the investiga tions reported here, the emphasis has been on circumferentia rather than radial or axial forces on the end-winding conductor

(3.2) Analysis of Force Distribution

From oscillographic records of the test, the appropriat instantaneous values of current were substituted into analyticall derived expressions for the circumferential forces adjacent t the knuckles of each coil. From these, the peak magnitudes i both directions attained over the first cycle were calculated a a function of coil position round the periphery, identificatio being by means of the slot number. The results are shown a an envelope by the two solid lines (*a*) in Fig. 4 which also show the position of the insulation failures in the upper layer. It ha already been pointed out that each coil experiences both its ow electromagnetic forces and also a certain transferred effect fron the whole end-winding structure. The mean force on any coi thus results from a combination of adjacent values in Fig. 4 and this makes it clear that the general tendency for the uppe layer is in a "positive" direction, which in this case represent contrarotational movement. The "negative" peaks are oppose to this main tendency so that coils where these peaks occu (e.g. 22, which failed) will be subjected to a series of oscillator movements of similar magnitudes in either direction, possibl resulting in only small or even no measurable final displacements This would seem likely to produce at least as much deterioratio of the insulation as a number of impulses in one direction, whicl approximates to what certain other coils would experience (e.g. 9 which also failed). The peak forces shown in Fig. 4 are not i time phase, each occurring at an instant determined by th maximum of an expression in the form of eqn. (2).

(4) SHORT-CIRCUIT TESTS ON AN EXPERIMENTAL STATOR

At the time of the incident referred to above, consideratio had already been given to the evolution of a means wherel the performance of any system of end-winding support coulc be assessed before its incorporation into a production machine As mentioned above, it is inherently difficult to evaluate th various constraints involved, and it was therefore felt that an form of scale model would probably not represent correctly th necessary relationships. The suggestion was considered that th conical form of the end winding could be developed—full-scale— into a plane for the purpose of experimental work. It wa decided, however, that the constraints would still not adequatel correspond to those in an actual machine; moreover the difficult

of arranging the conductors to obtain all the necessary currents n the correct relative positions and directions would have been n added complication to this form of apparatus. Such a simplified form of construction might be of value if it could first be hown to give results sufficiently similar to those obtained by nore accurate reproduction of the true conditions.

An important question arising at this time was whether correct epresentation of the stator currents alone would produce forces on the conductors equivalent to those occurring in an actual nachine under short-circuit conditions. In an alternator shortircuit the form of the magnetic fields in the end-winding region s influenced by the presence of the rotor, and in particular by he eddy currents in the retaining rings. The modifying effect of the rotor has been investigated and the results appear in Section 5. It is concluded that, compared with conditions proluced by the stator currents alone, the initial peak circumerential forces are lower during a short-circuit test, whereas the orresponding radial forces are higher. Since it appeared that ircumferential forces were responsible for the major damage aused to the conductor insulation it was decided that a true epresentation of the stator currents would permit the most mportant forces to be reproduced and even amplified; no ttempt was therefore made to include rotor effects during the xperimental-winding short-circuit tests.

(4.1) The Replica End-windings

The final form decided upon for the experimental work conisted of the full-size double-ended replica of the particular endvindings under examination. It was considered sufficient to nsure that the effect of the slot-embedded portion of the coils vas adequately represented and that the distance between the nd-windings was such as to make negligibly small any mutual lectromagnetic effects. Accordingly only 9 in axial length of ore-plates was employed, entailing a knuckle-to-knuckle coil ength of about 27 in, but in all other respects the apparatus esembled the complete alternator stator construction. A abricated framework was employed, and Fig. 5 shows a view f the completed stator replica. Different forms of end-winding upport were incorporated at the two ends of the replica; one f these was precisely as that employed, in the alternator menoned in Section 4, where 12 radial brackets located three upporting rings to which the windings were lashed. At the pposite end a different bracing was used, the major modificaon being to dispense with the three rings and to utilize 24 radial rackets, the coils being lashed to them direct. Since identical orces would be produced at corresponding points at the two nds a direct comparison would result. A series of short-circuit sts up to the equivalent of one at 80% rated voltage confirmed at the modified end was superior, and it was realized that in rder to obtain maximum information from the replica it was esirable to strengthen the other end before subjecting the indings to any greater forces. This was done before continuing e tests up to the 100% value.

(4.2) The Short-Circuit Tests

The experimental stator was subjected to instantaneous 3-phase ort-circuit tests, the current being supplied by a low-reactance vitchgear-testing alternator and controlled in magnitude by the ddition of external reactance in the circuit. The closure of the vitch applying the short-circuit was timed to occur at a point the voltage wave resulting in the greatest forces at particular ositions of the stator winding. A range of current values was osen, equivalent in magnitude to those resulting from shortrcuits at various voltages up to 100% on the original machine. scillographic records were taken of all the relevant electrical

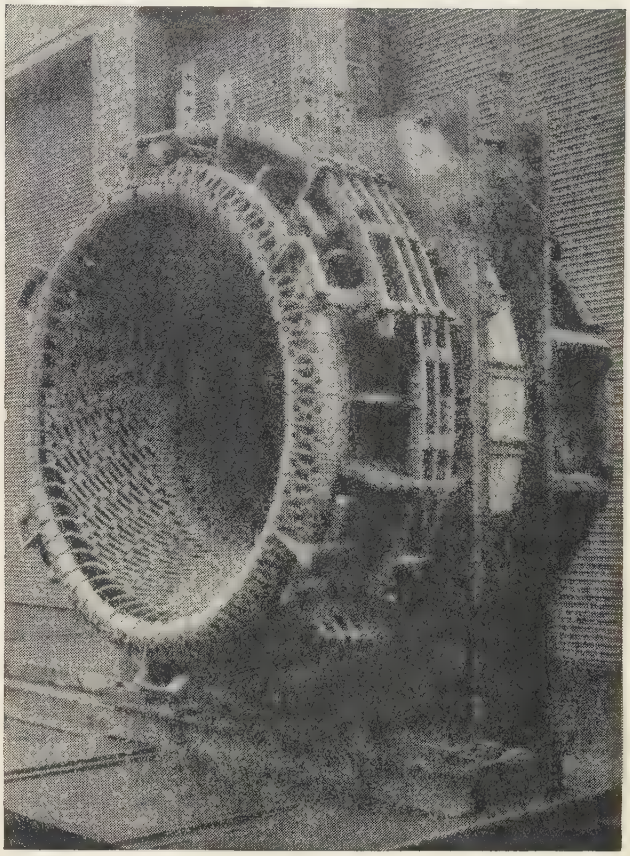

Fig. 5.—The replica stator subsequent to a test with currents equivalent to a full-voltage short-circuit on the alternator.

quantities and also of the output from eight devices indicating the mechanical movement of stator conductors relative to the core-plates and frame. A number of search coils recorded the alternating flux-densities occurring at various points in the endwindings. Numerous measurements were made with vernier callipers and other instruments before and after the tests.

Cinematograph records were made during the short-circuit tests. Two cameras were employed for this purpose, one recording at 64 frames/sec viewing the whole of the end-windings, and the second recording at 1 660 frames/sec viewing the core-endto-knuckle region of those conductors expected to experience the greatest forces in any particular test.

The movement-recording devices showed that up to currents equivalent to a short-circuit from 50% voltage, elastic deflections occurred on the conductors but no permanent deformations were caused. In further tests with currents equivalent to shortcircuits at 75% and 100% voltage the amplitude of the oscillations was greatly increased and some permanent deformation of the conductors resulted. Following the complete series of tests, the windings successfully withstood the full British Standard one-minute high-voltage insulation tests of twice working voltage plus 1 kV, both between phases and to earth.

A record was made of the distortions produced on the replica at the end braced as the original machine, and these are shown as curve (*c*) in Fig. 4 where they may be compared with the measurements taken on the original alternator. It is of interest to note the degree of correlation between these two results. The form and magnitude of the deflections are generally similar, somewhat more distortion having been produced on the replica. It must be borne in mind that a larger number of low-current

short-circuits was carried out on the replica than on the actual machine, and also that the rate of decrement was slightly lower during the experimental tests than that recorded on the alternator. As discussed below, the circumferential forces on the outer conductors of each phase band would be increased by the absence of the rotor.

Instantaneous deflections at points between the knuckles and the core at each end of four coils are shown in Fig. 6 for a test with currents equivalent to a full-voltage short-circuit. The points at which these measurements were made were nearer to the core than those to which Fig. 4 relates, and the permanent displacements shown do not correspond between Figs. 4 and 6. The peak displacements shown in Fig. 6 are seen to be con-

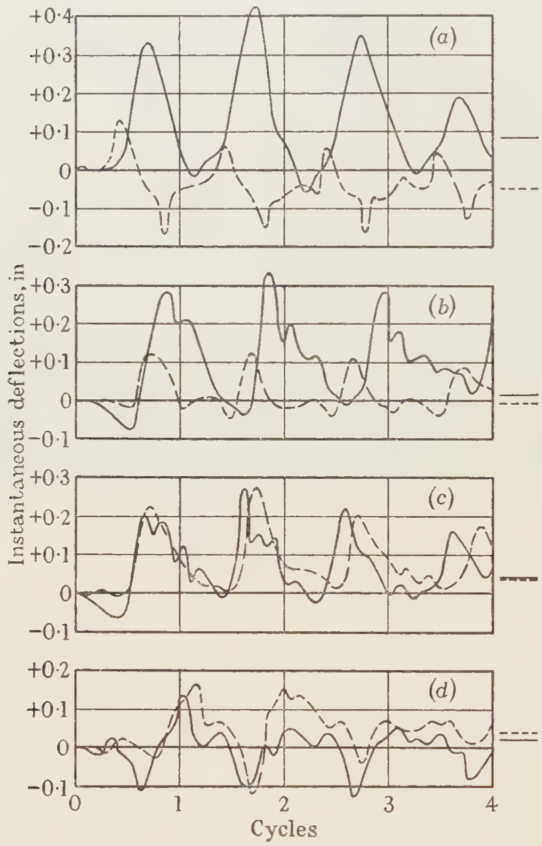

Fig. 6.—Instantaneous deflections measured at points between the knuckles and the core at each end of four coils during 3-phase short-circuit.

Coil numbers: (a) 41 (11); (b) 51 (21); (c) 20 (50); (d) 1 (31).
Initial 3-phase short-circuit current: 47 kA r.m.s.
Final positions indicated by lines at right.

——— Original bracing.
— — — Redesigned bracing.

siderably greater than the final permanent deflections indicated by the lines to the right of the Figure, and the complicated nature of the oscillation is evident. The latter may also be appreciated from the high-speed film, which strengthens the belief that analytical methods alone will hardly permit precise evaluation of end-winding performance.

(5) INVESTIGATIONS ON THE EFFECT OF THE ROTOR

It was evident that there might be differences in the forces experienced by the stator conductors when the same stator currents were produced (*a*) by short-circuiting an alternator running at rated speed and excited to produce some value c terminal voltage, and (*b*) by passing the same currents throug the windings from the external source with or without the roto in position. The configuration of the ordinary conical form c end-winding suggested that the effect of the rotor would diminis continuously from the coil knuckles out to the evolutes. Th investigations confirmed this tendency and attention agai centred on the knuckle-to-core region of the coils.

(5.1) D.C. Component of Stator Current

Fig. 7 shows graphically some measured flux-densities a functions of currents; these were obtained from two series c tests on an alternator stator with currents passed through th

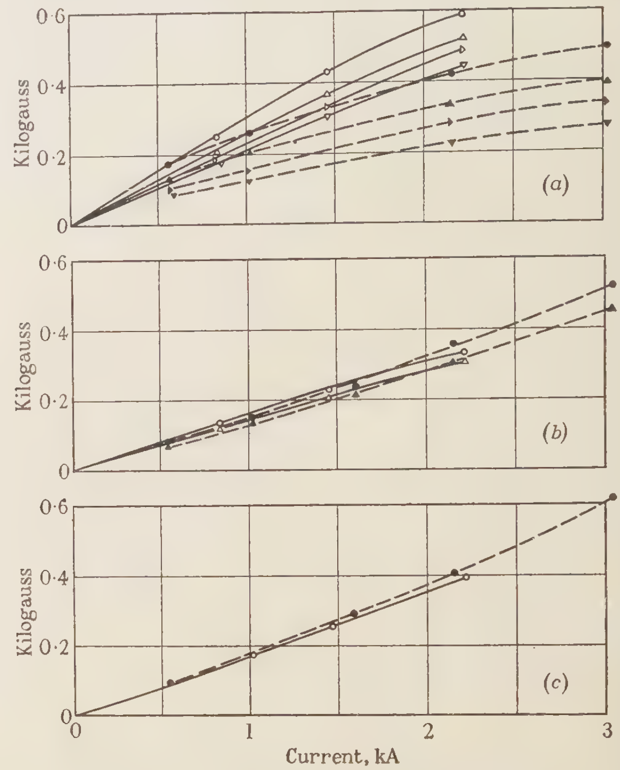

Fig. 7.—Variation of the fundamental alternating components of flu density with stator current.

(*a*) Radial components.
(*b*) Circumferential components.
(*c*) Axial components.
● Rotor in position (locked).
○ Rotor removed.

windings from an external source. In one series of tests th stator only was used while in the other the rotor was inserte into position but was held so that it was not free to rotate. I will be seen that the radial flux densities were lower in th presence of the rotor while those in circumferential and axia directions were slightly increased. Eddy currents in th stationary rotor and retaining rings oppose the establishmen of radial flux through the rotor by the stator field rotatin at fundamental frequency; the flux path is thus limited to th air-gap and the skin of the rotor iron. These conditions ar analogous to those occurring in an actual machine short-circui so far as the d.c. component of the stator current is concerned since in that case there is again a relative fundamental frequenc between the now stationary field and revolving rotor. Th circumferential forces on the stator conductors due to the fiel of the d.c. component of current would therefore be greater an the radial forces slightly lower on the replica tests than durin

a machine short-circuit resulting in currents of the same magnitude.

(5.2) A.C. Component of Stator Current

Two further series of search-coil measurements of flux density were taken during running short-circuits—series (i) up to 36% rated voltage on one of the machines upon which the replica was based, and in which the retaining rings were of magnetic material, and series (ii) up to 100% rated voltage on a 60-MW 11·8-kV 50-c/s alternator in which the retaining rings were of non-magnetic material. The results of series (i) are shown in Fig. 8 where they are compared with corresponding values

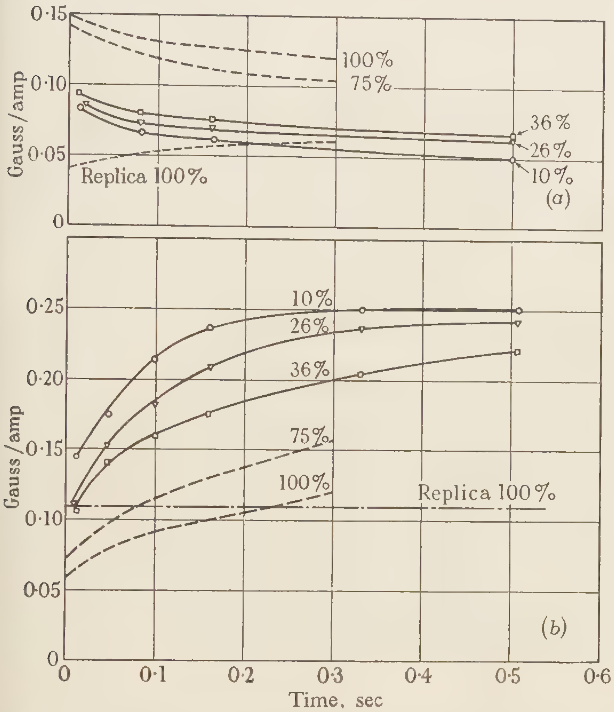

Fig. 8.—Variation of the flux density per ampere of stator current with time, measured at coil knuckles following the application of a 3-phase short-circuit on the replica stator and on a running alternator having magnetic retaining rings.

(a) Circumferential components.
(b) Radial components.

The figures on the curves relate to the percentage of rated voltage from which the short-circuits occurred.

measured in the replica. It will be seen that the initial values of radial flux density are again lower for the alternator tests. Eddy-currents flow in the main rotor body with an initial magnitude sufficient to maintain constant the flux-linkages existing prior to the short-circuit. A proportion of these currents passes axially into the retaining rings which also carry locally induced eddy-currents. The form of the fields in the neighbourhood of the stator-coil knuckles is determined by the configuration of current paths and iron surfaces, and the magnitudes of the currents vary interdependently in a somewhat complex manner. This case differs from that described in Section 5.1 in that both the rotating field and the rotor must now be considered to be revolving at the same speed, so that the phenomena are essentially similar to the build-up across an air-gap of a flux stationary in space and in the presence of iron circuits. Mathematical analysis of a configuration geometrically similar to the retaining-ring region of the machine at a cross-section through the coil knuckles gave results which agreed well with the measured values. The method employed in the calculation is outlined in Appendix 10.2.

With the decay of the eddy currents, flux penetrates the retaining rings, and where these are of magnetic material a maximum value of radial flux density per unit alternating stator current is reached at the coil knuckles which is greater than that obtained in the absence of the rotor. The flux density per unit current may be limited by saturation of the magnetic paths, and Fig. 8(b) indicates the effect that this has on the rate of growth of the radial field.

Fig. 9 illustrates the calculated behaviour of the flux entering the magnetic retaining ring and shows the effect of saturation.

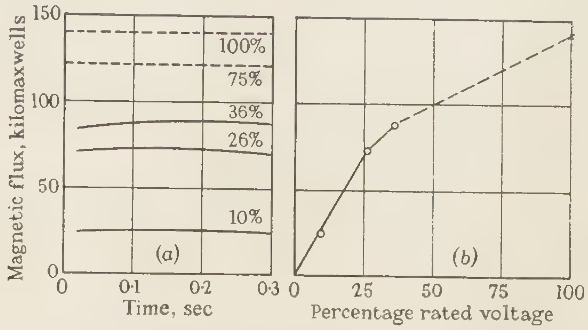

Fig. 9.—The flux entering the retaining ring as a function of time and of applied voltage during 3-phase short-circuits.

In the results of test series (ii) carried out on the machine having non-magnetic retaining rings, the flux-density/current curves differed from those shown in Fig. 8 in that the results were practically independent of the magnitude of the current and tended to a limit corresponding to the value given by tests on the stator alone. The initial radial and circumferential components were about 85% and 115%, respectively, of their limiting values, which were reached after only a few cycles of short-circuit current. This time is of the same order as that taken for the decay of the eddy currents in the rotor body, and it is evidence of the fact that some of these currents flow into the retaining ring in their passage round one pole pitch to where they re-enter the main rotor body in the opposite axial direction.

Fig. 10 has been prepared from Fig. 8(b), and shows, as a function of time, a comparison of the peak circumferential forces calculated to occur on the replica and those in a short-circuit in the alternator from 100% voltage on open-circuit. For the

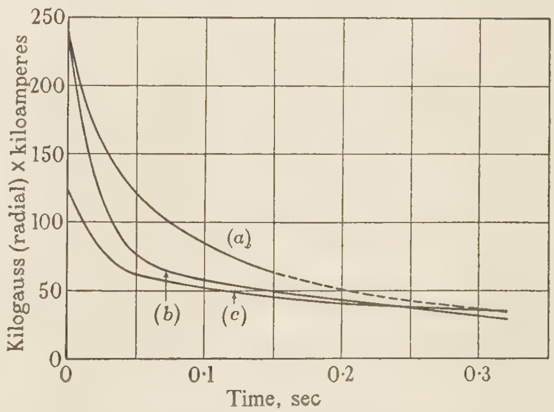

Fig. 10.—Variation of product of current and radial flux density with time during short-circuit from rated voltage.

	Current	Flux density
(a)	Measured in replica test	Measured in replica test
(b)	Measured in alternator	Measured in replica test
(c)	Measured in alternator	Calculated value for alternator

latter figures account has been taken of saturation in the iron paths. It will be seen that the replica tests produce higher initial circumferential forces but that the final sustained value is greater in the alternator. The measurements taken during the replica tests referred to in Section 4 indicated that, in respect of probable damage to conductors, by far the most significant current values were those in the range equivalent to short-circuits from 75 to 100% voltage. Fig. 8(*a*) indicates that for such short-circuits the peak radial forces acting initially on the stator conductors are larger on the alternator than those reproduced on the replica. The main radial forces are directed outwardly, and the two layers of the end-winding are very effectively supported by brackets bolted to the core. In addition, the normal form of stator construction is such that the winding assembly can be regarded as forming a composite whole which may then be several times stronger to bending in a radial direction than in a circumferential direction.

The results obtained from flux-density measurements on alternators during short-circuit confirm that equal current tests on a replica represent more severe conditions with respect to possible insulation damage.

(6) THE EFFECT OF THE TYPE OF SHORT-CIRCUIT

In Section 2 a description is given of the analytical expressions for the forces occurring at points in the end-winding structure. These take the form of eqn. (2) and are in terms of all three phase currents. In order to assess the severity of different types of short-circuit it is necessary to ascribe relative values to the *k* coefficients.

To simplify the problem it has been assumed that eqn. (2) takes the form

$$F = k_{11}I_1^2 + k_{12}I_1I_2 \quad . \quad . \quad . \quad . \quad . \quad (3)$$

It can be seen from Fig. 3 that at many points it is reasonable to neglect one coefficient in comparison with the other two. On this basis Fig. 11 has been prepared showing the peak values over the cycle of this expression for force. The curves are directly comparable if the current in a single-phase-to-earth fault is limited by neutral impedance to the same value as that in a 3-phase short-circuit. If the ordinates are considered to be multiples of k_{11} or k_{12} whichever is the larger, the curves then represent the maximum possible values of *F*. The figures are given as a function of the angle ψ after a voltage zero at which a solid fault is assumed to occur, and include the following types of short-circuit:

(*a*) A simultaneous 3-phase short-circuit where ψ refers to V_{1-N}.
(*b*) A phase-to-phase short-circuit where ψ refers to V_{2-3}.
(*c*) Single-phase-to-earth short-circuits occurring sequentially and at the same angle ψ of each phase-to-neutral voltage.
(*d*) A breakdown from phase 1 at an angle ψ on $V_{1-2,3}$ to an existing phase-to-phase fault between phases 2 and 3, which occurred at an angle ψ on V_{2-3}.

It will be seen that except for case (*a*) the forces vary over a considerable range with changes in the angle at which the short-circuit occurs. In practice, the great majority of the faults which may arise are associated with breakdown of solid insulation or flashover in air between conductors. In neither case is it possible for failure to occur at zero voltage (i.e. $\psi = 0$), and as can be seen from the curves, for cases (*b*), (*c*) and (*d*) the forces fall off rapidly with increasing voltage (i.e. as the currents become more nearly symmetrical). In case (*a*) the maximum force occurs when one phase breaks down at a voltage peak, which implies a symmetrical current in that phase if the impedance is purely inductive. The peak force occurs half a cycle later when the remaining two phases both carry an instantaneous current equal to $\sqrt{(3)}I$, where *I* is the peak value of the a.c. component. It will be noticed that the minimum value of force for case (*a*) is 85% of the maximum compared to corresponding figures of 25%, 14% and 18% for cases (*b*), (*c*) and (*d*).

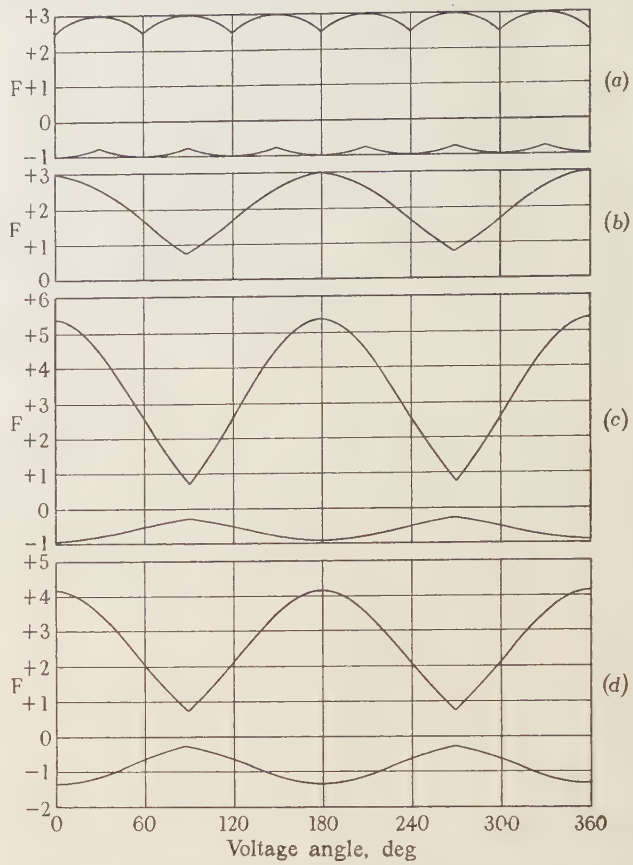

Fig. 11.—Relative values of the peak circumferential forces, *F*, as functions of the voltage angle ψ at which the short-circuit occurs.

(*a*) A simultaneous 3-phase short-circuit (ψ refers to V_{1-N}).
(*b*) A phase-to-phase short-circuit (ψ refers to V_{2-3}).
(*c*) Single-phase-to-earth short-circuits occurring sequentially and at the same angle ψ on V_{1-N}, $-V_{3-N}$, V_{2-N}.
(*d*) Short-circuit from phase 1 at a voltage angle ψ to an existing phase-to-phase fault between phases 2 and 3 which occurred at angle ψ on V_{2-3}.

An additional factor tending to reduce the current magnitudes is the resistance of the arc which will occur in any form of insulation breakdown. Experimental work has provided a measure of the reduction due to this cause. A test circuit was set up to produce at 11 kV a prospective current of 47 kA resulting from a solid 3-phase short-circuit. It was then arranged that the short-circuits occurred with arcs of varying lengths in the current paths. Since the initiation of the arc was obtained by means of fuse-wire, maximum asymmetry resulted. The peak currents recorded are shown in Fig. 12 as a function of the arc lengths and with the ordinates expressed as percentages of the current in the solid short-circuit. It will be seen that with arcs of a length likely to be encountered in practice, a current of about 75–80% of that in a solid short-circuit would result. Thus, when the effect of both the arc resistance and the decrease in asymmetry are taken into account, a considerable reduction in current results compared with the theoretically worst case. A reduction to about 66% may be expected, and since the forces vary as the square of the current the corresponding reduction in forces would be to less than half the values shown in Fig. 11.

Another eventuality on power systems which may have to be considered is the possibility of the inadvertent closing of a

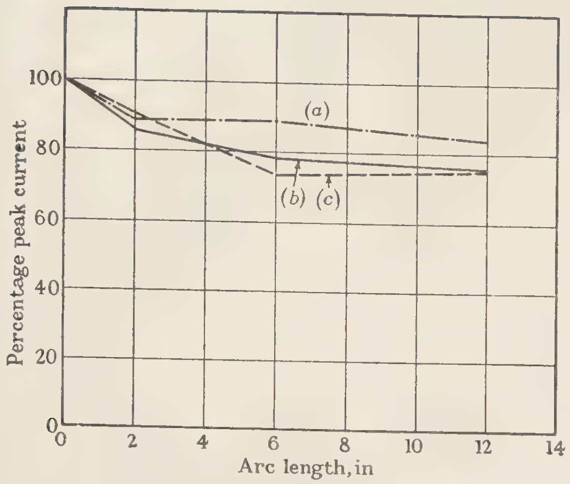

Fig. 12.—Illustrating the decrease in short-circuit current with arc length.

Peak currents measured in each phase as percentages of those in a solid short-circuit.

(a) Blue phase.
(b) Red phase.
(c) Yellow phase.

machine on to a system 180° out of phase. The currents resulting from such an operation are those produced by an effective voltage of twice the normal value acting across an impedance equal to the sum of the machine and system impedances. In the situations where this might result in dangerously heavy currents, the generator will almost always be connected to the system via a generator transformer. An examination of typical reactances for this case shows that even at locations having the highest short-circuit levels the currents will be only about 80% of those resulting from a solid short-circuit on the generator at normal voltage, with corresponding reduction to about 66% of the forces on the conductors.

(7) CONCLUSIONS AND RECOMMENDATIONS

With the present tendency to increase sharply the size of individual units, it would now seem opportune to examine carefully all available records concerning types of faults experienced in service with a view to arriving at a more realistic winding-bracing test before despatch.

Information on such records has been requested from the headquarters staff of the British Electricity Authority. On the subject of faults on the low-voltage side of generator transformers, including connections, terminals, etc., the instances of phase-to-phase faults which they have recorded comprise the following:

Ten occasions where flashovers took place on copper-work between the terminals of the generator and the transformer due to various causes such as vermin, water and failure of cable-boxes, etc.

Two cases where breakdowns between phases occurred inside the main generator transformer on the low-voltage side.

One case where the unit auxiliary transformer broke down.

In addition there have been a number of failures between phases on the end-windings of generators.

Since in all cases flashovers are involved, and it is difficult to see how it could be otherwise, any test before dispatch could take the form of a flashover at normal voltage initiated by fuses; alternatively, a solid short-circuit at reduced voltage could be applied, since such a test may in any case be required to check the alternator reactance.

If, after reviewing available data, it is still felt that the stator windings should be proved capable of withstanding a solid short-circuit at the machine terminals from normal voltage on open-circuit, it may be considered that such a proving test should be applied not to the actual windings but to a short-cored, but otherwise full-scale, replica of the windings as made. A full-voltage short-circuit applied to the actual generator windings, to the customer's satisfaction, might well cause insulation damage which, although not immediately apparent, would lessen the ability of the machine to withstand the less severe but more frequent forces likely to be experienced under actual fault conditions in service. The use of a replica would ensure that the windings of the machine as delivered would be in a new condition. Assuming that a sufficiently large source of power were obtainable, a replica winding would, in addition, permit testing to destruction to be carried out, thus providing the designers and users of machines with an indication of the margins available. The disadvantage of this procedure would be the cost and the time involved in manufacturing and testing such a replica. It should be clearly understood that the above suggestions are made in the best interest of the customer from the point of view of reliability of machines in service and not to obtain any relaxation in actual bracing effort for the manufacturer.

Available information regarding American practice is that while manufacturers brace machine end-windings to comply with specifications, they do not as a general rule carry out instantaneous short-circuit tests on turbo-alternators. They are, however, prepared to do so should such a requirement be written into the contract, but for reasons similar to those outlined above, customers are not encouraged to call for such tests. The general indications, therefore, are that in America short-circuit tests are rarely applied.

It is hoped that the film taken of the struggling windings under short-circuit conditions will make clear the undesirability of subjecting the coils and insulation to forces appreciably greater than they are likely to experience under any condition in service.

(8) ACKNOWLEDGMENTS

The authors wish to thank the English Electric Company for permission to publish the paper; they are glad to acknowledge their indebtedness to the Headquarters Staff of the British Electricity Authority for supplying statistics, and to their colleagues at the Company's Stafford Works, the Director of Research and the staff of the Nelson Research Laboratories for facilities and assistance in carrying out the investigations reported.

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(10) APPENDICES

(10.1) Calculation of the Coefficients in the Expression for Force (Equation 2)

End-winding dimensions are determined by the bore diameter and length of the stator, the coil pitch and the requirement of

suitable spacing between adjacent conductors. In the machine selected for the calculation, both layers of the end-winding formed cones coaxial with the stator, and the spacing between adjacent coils was constant over their length. For the calculation, the conductors were considered to be replaced by line circuits through their centres.

In a plane development of the windings, an approximate expression in polar form for the coil shape was found to be

$$r = R\epsilon^{k(\theta \pm n\delta)/r} \quad . \quad . \quad . \quad . \quad . \quad . \quad (4)$$

where R, k and δ are constants for one layer of the winding and n defines the position of the coil relative to a given reference coil (for which $n = 0$).

It has been shown[3,4] that the magnetizing force in, say, the y-direction, at a point P, due to current flowing through a line circuit in 3-dimensional space, is proportional to an area swept over by a vector in the xz-plane through P. Consider the projection C′ of a line circuit C on to the xz-plane through the point P. From P draw in the direction of each point Q′ of the projection C′ (corresponding to a point Q on C) a vector of length

$$\rho = \frac{PQ'}{(PQ)^{\frac{3}{2}}} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (5)$$

The area required is that swept over by such vectors, as Q moves from one end to the other of the circuit C.

It is required to calculate, at a number of points P along the length of the reference coil, the magnetizing force due to unit current in all coils of the end-winding. Consider the position of one such point P in the plane development and let it be represented there by (r_P, θ_P); consider also a general point Q, (r, θ), on a coil whose effect at P is being calculated. If the origin is taken at the apex of the cone the co-ordinates of any point (r, θ) become

$$\left.\begin{aligned} x &= r \sin\phi \sin\sigma \\ y &= r \sin\phi \cos\sigma \\ z &= r \cos\phi \end{aligned}\right\} \quad . \quad . \quad . \quad . \quad . \quad (6)$$

where ϕ is the half-angle of the cone and $\sigma = \theta/\sin\phi$.

Let the co-ordinates of the point P be (x_P, y_P, z_P) and let

$$\left.\begin{aligned} X &= x - x_P \\ Y &= y - y_P \\ Z &= z - z_P \end{aligned}\right\} \quad . \quad . \quad . \quad . \quad . \quad . \quad (7)$$

Then $$(PQ)^2 = X^2 + Y^2 + Z^2 \quad . \quad . \quad . \quad . \quad . \quad (8)$$

and for the calculation of H_y,

$$(PQ')^2 = X^2 + Z^2 \quad . \quad . \quad . \quad . \quad (9)$$

and $$\rho^2 = \frac{X^2 + Z^2}{(X^2 + Y^2 + Z^2)^{\frac{3}{2}}} \quad . \quad . \quad . \quad . \quad (10)$$

If $\tan\xi = X/Z$ an increment of area swept over by ρ is given by

$$dA = \frac{1}{2}\rho^2 d\xi = \frac{1}{2}\frac{ZdX - XdZ}{(X^2 + Y^2 + Z^2)^{\frac{3}{2}}} \quad . \quad . \quad . \quad (11)$$

Since X, Y and Z are known in terms of r and the co-ordinates of P, eqn. (11) can be written as

$$dA = f(r)dr \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (12)$$

In general, the expression $f(r)$ is not amenable to explicit integration; the value of A must be obtained by numerical integration between the appropriate limits of r representing the movement of the point Q from one end to the other of the coil C whose effect at P is being calculated. The area A is proportional to H_y at P due to C. Similar treatment enables expressions to be derived for H_x and H_z, and also the components due to the straight coil extensions from the slots, these being directly integrable between suitable limits. The components of H_x, H_y and H_z due to coils carrying currents of the same phase can be combined, and hence the magnetic flux densities B_x, B_y and B_z at P are obtained in terms of the three phase currents I_1, I_2 and I_3.

It is necessary to determine at P the direction cosines $\cos\alpha$, $\cos\beta$ and $\cos\gamma$ of the current I_1 in the reference coil; these can be obtained in terms of r, θ and ϕ, and can be evaluated.

The forces at the point P per unit length of conductor are then given by

$$\begin{bmatrix} F_x \\ F_y \\ F_z \end{bmatrix} = I_1 \begin{bmatrix} 0 & -\cos\gamma & \cos\beta \\ \cos\gamma & 0 & -\cos\alpha \\ -\cos\beta & \cos\alpha & 0 \end{bmatrix} \begin{bmatrix} B_x \\ B_y \\ B_z \end{bmatrix} \quad . \quad (13)$$

But $$\begin{bmatrix} B_x \\ B_y \\ B_z \end{bmatrix} = \begin{bmatrix} b_{11} & b_{12} & b_{13} \\ b_{21} & b_{22} & b_{23} \\ b_{31} & b_{32} & b_{33} \end{bmatrix} \begin{bmatrix} I_1 \\ I_2 \\ I_3 \end{bmatrix} \quad . \quad . \quad (14)$$

where $b_{11} \ldots b_{33}$ result from the calculations described above.

Substituting eqn. (14) in eqn. (13) gives

$$\begin{bmatrix} F_x \\ F_y \\ F_z \end{bmatrix} = I_1 \begin{bmatrix} k_{11} & k_{12} & k_{13} \\ k_{21} & k_{22} & k_{23} \\ k_{31} & k_{32} & k_{33} \end{bmatrix} \begin{bmatrix} I_1 \\ I_2 \\ I_3 \end{bmatrix} \quad . \quad . \quad . \quad (15)$$

i.e. $F_x = k_{11}I_1^2 + k_{12}I_1I_2 + k_{13}I_1I_3$, etc., where $k_{11} = -b_{21}\cos\gamma + b_{31}\cos\beta$, etc.

The terms $k_{11} \ldots k_{33}$ were evaluated at a number of points along the reference coil and the results are shown graphically in Fig. 3.

(10.2) Analysis of an Equivalent Two-Dimensional System

Fig. 13(*a*) shows a drawing of the end-winding region of a turbo-alternator. The system analysed represents a section through the stator-coil knuckles as indicated. Fig. 13(*b*) shows the equivalent system assumed. The effect of the stator winding is represented by a current sheet located at the mean radius R_3 of the conductors. This current sheet has a sinusoidally distributed m.m.f. equal to the fundamental component associated with the a.c. stator current, I, and given by

$$M = IM_0 \cos\theta \quad . \quad . \quad . \quad . \quad . \quad (16)$$

where M_0 is a function of the stator-winding parameters and has a value of 15·7 gilberts/amp for the machine considered. The magnetic retaining-ring and the proximity of the stator iron are represented by iron surfaces at, respectively, a known radius R_1 and a radius R_2 to be given a suitable value consistent with test results.

It is required to determine the flux distribution in the annular air-space between the two cylindrical iron surfaces in the presence of the concentric current sheet. In regions (i) and (ii) of Fig. 13(*b*) the following equations can be written relating the radial, B_R, and circumferential, B_θ, components of magnetic flux density at any point (R, θ)

$$\left.\begin{aligned} \frac{\partial B_\theta}{\partial\theta} + B_R + R\frac{\partial B_R}{\partial R} &= 0 \\ R\frac{\partial B_\theta}{\partial R} + B_\theta - \frac{\partial B_R}{\partial\theta} &= 0 \end{aligned}\right\} \quad . \quad . \quad . \quad . \quad (17)$$

The general solutions[5] for eqns. (17) are

$$\left.\begin{aligned} B_R &= (C_1R^{n-1} + D_1R^{-n-1}) \sin n(\theta - \theta_1) \\ B_\theta &= (C_2R^{n-1} + D_2R^{-n-1}) \sin n(\theta - \theta_2) \end{aligned}\right\} \quad . \quad (18)$$

the constants having different values in regions (i) and (ii).

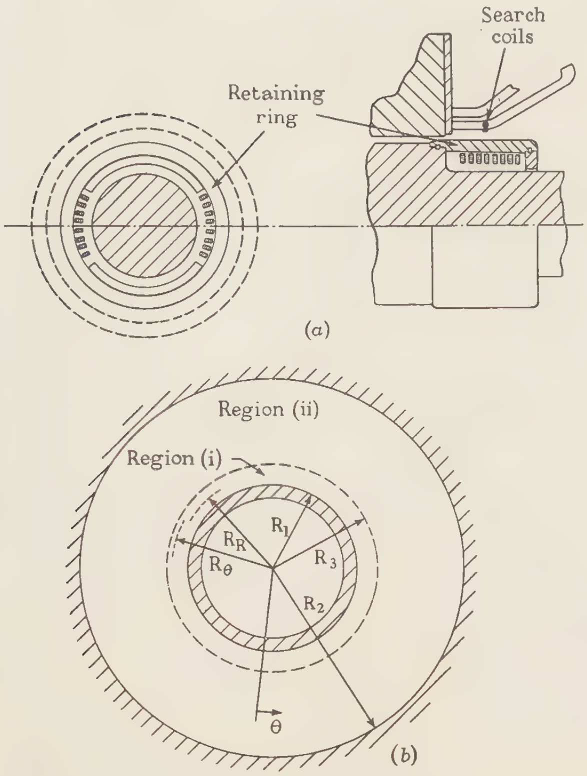


Fig. 13.—Relevant to the analytical representation of an approximate equivalent system.
(*a*) Alternator sections at retaining ring.
(*b*) Two-dimensional model to same scale.

The boundary conditions are

$$\left.\begin{aligned} B'_\theta &= 0 && (R = R_1) \\ B''_\theta &= 0 && (R = R_2) \\ B'_R &= B''_R && (R = R_3) \\ B'_\theta - B'_\theta &= \frac{1}{R_3}\frac{d}{d\theta}(M_0 \cos\theta) && (R = R_3) \end{aligned}\right\} \quad . \quad (19)^*$$

Considering these conditions and the current sheet at R_3 with m.m.f. of value $IM_0 \cos\theta$, the solutions to eqns. (18) take the form

$$\left.\begin{aligned} B'_R &= -\frac{IM_0(R_3^2 + R_2^2)}{2R_3(R_2^2 - R_1^2)}\left(1 + \frac{R_1^2}{R^2}\right)\cos\theta \\ B'_\theta &= \frac{IM_0(R_3^2 + R_2^2)}{2R_3(R_2^2 - R_1^2)}\left(1 - \frac{R_1^2}{R^2}\right)\sin\theta \\ B''_R &= -\frac{IM_0(R_3^2 + R_1^2)}{2R_3(R_2^2 - R_1^2)}\left(1 + \frac{R_2^2}{R^2}\right)\cos\theta \\ B''_\theta &= \frac{IM_0(R_3^2 + R_1^2)}{2R_3(R_2^2 - R_1^2)}\left(1 - \frac{R_2^2}{R^2}\right)\sin\theta \end{aligned}\right\} \quad . \quad (20)$$

* In these equations ′ refers to region (i) and ″ to region (ii).

From search-coil records on the alternator, values of B_R (at $R = R_R$) and B_θ ($R = R_\theta$) were available corresponding to low currents and steady-state conditions. A particular value of R_2 was found which when substituted in eqns. (20) with the values of R_1, R_3, R, M_0 and I gave results corresponding closely with the test figures. It can be seen from Fig. 13(*b*) that the value of R_2 represents approximately a mean path to the end of the stator iron. Using this value of R_2 and setting $R_1 = 0$ to represent the removal of the rotor resulted in values of B_R and B_θ agreeing reasonably well with those measured on the replica stator tests.

In order to represent the effect of saturation and eddy currents in the retaining ring, a current sheet is introduced at $R = R_1$ having an m.m.f. of value $-\lambda M_0 \cos\theta$. This results in modification of the results in eqn. (20) for region (i), these now taking the form

$$\left.\begin{aligned} B'_R &= \frac{-M_0}{(R_2^2 - R_1^2)} \left[\frac{(R_3^2 + R_2^2)}{2R_3}\left(1 + \frac{R_1^2}{R^2}\right)I - R_1\left(1 + \frac{R_2^2}{R^2}\right)\lambda\right]\cos\theta \\ B'_\theta &= \frac{M_0}{(R_2^2 - R_1^2)} \left[\frac{(R_3^2 + R_2^2)}{2R_3}\left(1 - \frac{R_1^2}{R^2}\right)I - R_1\left(\frac{R_2^2}{R^2} - 1\right)\lambda\right]\sin\theta \end{aligned}\right\} \quad (21)$$

or, substituting the numerical values of the parameters

$$B_R = 0{\cdot}260I - 0{\cdot}276\lambda \text{ r.m.s.} \quad (R = R_R) \quad . \quad . \quad (22)$$

$$B_\theta = 0{\cdot}045I - 0{\cdot}142\lambda \text{ r.m.s.} \quad (R = R_\theta) \quad . \quad . \quad (23)$$

$$B_R = 0{\cdot}415I - 0{\cdot}478\lambda \text{ peak} \quad (R = R_1) \quad . \quad . \quad (24)$$

Half the total flux entering the outer surface of the retaining ring per unit axial length is given by

$$\Phi = R_1 \int_0^{\pi/2} B_R d\theta = 20I - 23{\cdot}1\lambda \quad . \quad . \quad . \quad (25)$$

or

$$\lambda = 0{\cdot}866I - 0{\cdot}0434\Phi \quad . \quad . \quad . \quad . \quad (26)$$

Substituting this expression for λ in eqns. (22) and (23) gives

$$B_R = 0{\cdot}021I + 0{\cdot}012\Phi \quad . \quad . \quad . \quad . \quad (27)$$

$$B_\theta = 0{\cdot}168I - 0{\cdot}00615\Phi \quad . \quad . \quad . \quad (28)$$

From short-circuit tests and search-coil records on the alternator, values of Φ were calculated. These are shown in Fig. 9, and indicate that for any given test, Φ remains approximately constant for times of the order of 0·3 sec following the short-circuit, and also that saturation will impose an upper limit to Φ for the higher short-circuit currents. A pessimistically high value was assumed for this limit, and the flux densities and forces were calculated for a 3-phase short-circuit from 100% rated voltage. The result is shown in Fig. 10 where it is compared with conditions occurring in the replica stator during a test with similar currents.

DISCUSSION BEFORE THE SUPPLY SECTION, 15TH DECEMBER, 1954

Mr. L. W. James: The authors have brought forward the paper at an opportune moment, since on the supply side we shall shortly be faced with the problem of testing and installing the first of a large number of 100/120 MW 3 000 r.p.m. generators.

The works tests specified for these machines call for, amongst other things, a sudden 3-phase short-circuit test at the machine terminals at normal voltage. This test is carried out mainly as a check on the strength of the machine windings and bracing, and whilst we have never been unduly worried at the prospect of such tests, it is very pleasant to know that the authors have carried out tests on a replica winding to show that machines of 100 MW rating can apparently be braced to withstand satis-

factorily the forces set up by the heavy currents arising from full-voltage 3-phase short-circuits, without undue weakening of the insulation.

It might be argued that this must have already been proved in other countries where machines much larger than 100 MW have been running for some time now, but this does not necessarily follow, since, for instance, although the standard American Rules state that a generator shall be capable of withstanding a sudden 3-phase short-circuit at the terminals at 5% above normal voltage, it appears that for many years it has not been the practice either for the makers to carry out such tests for their own information on new designs, or for the purchasers to specify them to prove that this requirement has been met.

During my early training in turbo-generator design in the electrical manufacturing industry, I was taught to consider full-voltage short-circuit testing as a standard routine test, certainly to be carried out for information on bracing strength and on reactance values, in every case where a new design was produced or an old design modified. I may therefore be somewhat biased in dealing with this question.

But so far as I am aware, on machines which have passed all their tests satisfactorily, no troubles have later occurred which could in any way be considered as due to the short-circuit tests.

It is known, however, that some machines which have never had their design tested in this way have later broken down owing to collapse of windings when subjected to short-circuit faults, and the expense and outage then necessary to repair a machine after it has been installed on site is very much more serious than that necessary to put in additional bracing and blocking if signs of weakness are shown during the works short-circuit tests.

The authors suggest that whilst such testing was necessary when machines fed local systems at generated voltage it may no longer be really necessary on the large generator-transformer units now being commissioned. If system or busbar faults were the only troubles to be expected, this might be reasonable, but faults on machines, their connections or the transformer windings still occur—all too frequently from our point of view. We also want a reasonable margin to take care of deterioration of bracing during 25 years' life.

Added to this there can be no guarantee that the terminal voltage will never exceed the normal value, and should the main switch trip when a machine is carrying full load with the voltage regulator out of action, voltages 50% or more above normal can occur. If a winding fault is likely at all, it will occur under such conditions, and then, even allowing for the various effects which can reduce the currents below those of a solid short-circuit at the terminals, currents of the same order as those of a 3-phase full-voltage short-circuit may arise.

It therefore appears that, although such happenings may be extremely rare, it is still desirable to have a test to prove that the windings will not collapse and necessitate a complete rewind instead of a relatively simple repair.

In view of the unlikely event of such serious trouble, however, it is considered that a full-voltage test need be carried out only on the first machine of a new design, or whenever a modification is made to a winding or its bracing. Similarly, it appears reasonable to accept a test on a replica winding, such as indicated in the paper, as sufficient proof of the strength of a machine with duplicate coil section and bracing, particularly where coupled with a check on the machine and replica movement at some reduced voltage considered to be perfectly safe. If, in addition to such tests, a reasonable number of duplicate machines are short-circuit tested at about half-voltage to give a check on the sub-transient reactances required for system switchgear calculations, this should be sufficient.

If at any time it is considered that short-circuit currents are becoming too high, there appears to be no objection to a reasonable increase in reactance.

I note the authors propose that replica tests at current values below those of a solid full-voltage 3-phase short-circuit, or machine tests at reduced voltages, could become a suitable standard test to meet all reasonable requirements. Yet they have tested a 100/120 MW replica at the equivalent of full voltage without any apparent difficulty. Is it with the larger sets of 200 MW and above that they would like to reduce this test?

If this did prove to be acceptable, what advantage could be given to the purchaser to compensate for the reduced factors of safety on the windings? Would it be possible to offer any financial incentive or perhaps a reduction of stray loss or overall length of windings? If not, I feel that we should insist on a prototype test either on the first machine, or a replica, at full voltage while it is still a practical proposition to do this.

Mr. W. N. Kilner: The authors have shown very clearly the order of magnitude of the forces which occur in the end-windings of turbo-alternators under conditions of sudden short-circuit. The problem of satisfactorily bracing the end-windings is greatest in the case of 2-pole machines, because they normally have higher stator ampere-turns per pole than 4-pole or multi-pole machines, and also their reactances are lower, so that, on short-circuit, the corresponding currents are higher.

The modern trend is towards the use of larger machines, and they are nearly all of the 2-pole type. They are also hydrogen-cooled, and the use of hydrogen enables the specific rating in terms of ampere-turns on the stator to be considerably increased, so that the ampere-turns per pole are again higher than on air-cooled machines. The forces likely to be encountered on future machines will therefore be considerably higher than on existing machines.

My colleagues and I have carried out sudden short-circuit tests at full voltage on some hundreds of turbo-alternators, with various types of end-winding bracing. We have therefore been able to collect a large quantity of data regarding the effectiveness of different types of end-winding support. During the past 10 years, 50 machines have been tested which have exceeded 40 000 kVA normal capacity, and four were 60 MW hydrogen-cooled generators. During the past 10 years only one stator winding breakdown has occurred on voltage test after the short-circuit test, and this was only a minor breakdown which was very quickly repaired.

In spite of this experience and the good results of the tests, I do not think it would be good practice to carry out such tests on the larger machines of the future.

Most manufacturers provide a margin on the end-winding insulation to allow for the fact that some deterioration must take place during the 20 or 30 years' life of the machine. There is a danger that a sudden short-circuit test at full voltage may take away some of this margin. The punishment which the insulation receives from the forces which cause movement must adversely affect the life of the insulation. If tests are made, I would strongly recommend that they should be done with the windings warm, because I believe the damage to the insulation will then be less than if the windings are cold. My observations of windings leave me to believe that the forces are greater on the top layer than on the bottom layer of involute-type windings, and it would be interesting to know whether this is also the authors' experience.

The authors imply that the greatest improvement they made in the model winding, was to do away with the support rings and increase the number of radial brackets. I believe that the strength of the windings is more dependent upon the careful arrangement of the small blocks between coils, and particularly the taper blocks between the straight parts of the bars where

they project from the end of the core, between the end of the core and the knuckles. I should like to hear from the authors whether the improvements that were made after the original test included additional blocking.

Fig. A shows part of the end-windings of a stator which was put into service sixteen years ago, and which was given a sudden

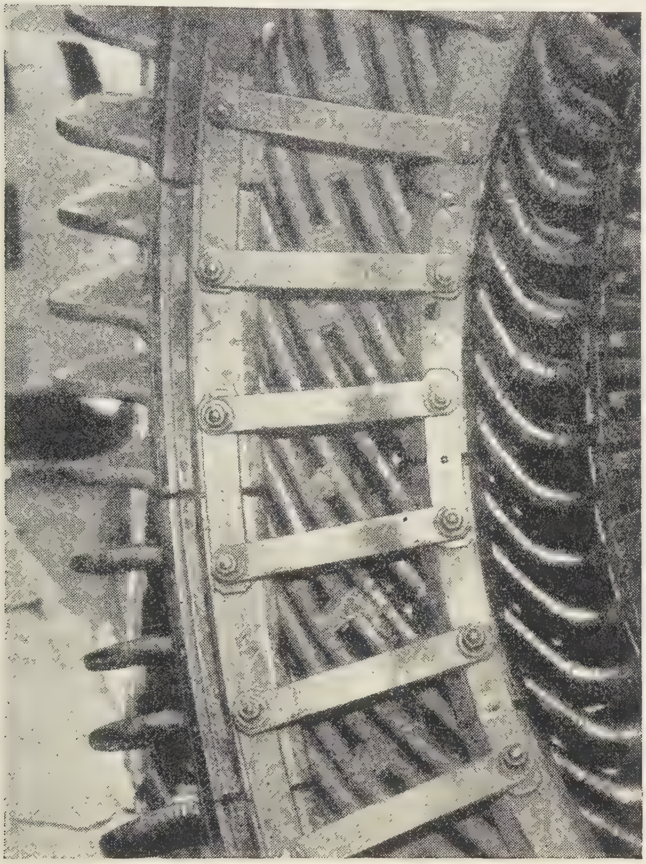


Fig. A

short-circuit test at full voltage before shipment. It shows how parts of the winding were displaced as a result of this test. The stator was not rewound, but the windings were warmed and the coils gently moved and spacing blocks fitted between them to provide the necessary ventilation and give additional support. The winding did not break down on the official voltage test and has operated satisfactorily ever since.

Fig. B shows the stator winding of a similar machine with the same type of bracing, but with a larger number of small packing blocks between coils. The windings are supported on brackets similar to those used by the authors, but they are clamped between circumferential rings, and pulled down on to the brackets by steel bolts. I feel that this is a better way of securing the winding than lashing it to the brackets with cord. Fig. B also shows the row of blocks just outside the core, which give exceptionally good support to the overhanging straight parts of the coils. This stator withstood a sudden short-circuit test at full voltage without any distortion of the winding.

Finally, although we know how to brace windings to prevent movement, I am not happy about subjecting the insulation to unnecessarily high mechanical forces. My recommendation would be that there should be some compromise for machines of the order of 100 MW, and if the users wish to have some assurance that there is not something inherently wrong in the machine construction, they should make a test at about 75–80% voltage. I am not in favour of model tests, because the workmanship is such an important factor in determining the effective-

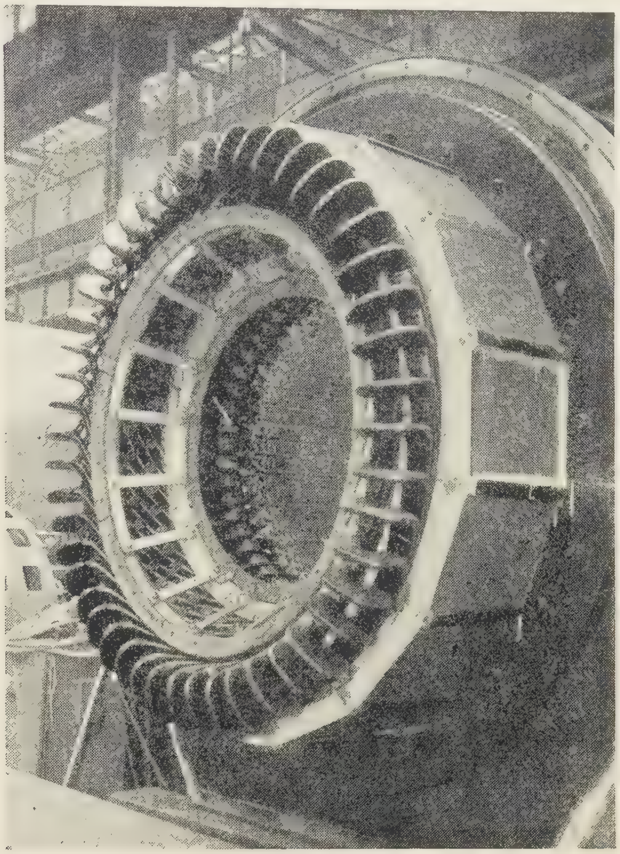


Fig. B

ness of the bracing, and the model test does not prove the workmanship of the actual machine.

Mr. F. C. Winfield: The authors have attempted to make a mathematical investigation, but this make-up of wood, string and paper, and part-rigid support and part-no-support, is an utterly indeterminate mechanical structure, and it is little use trying to do anything except by way of experience, test and practical investigation. The authors' attempt at a model test was something in this direction.

But the authors are really posing to the user, in particular, the question "What shall we do; ought we not to reduce these tests?"

Let us start by considering the 60 MW set. We have plenty of examples of full-scale short-circuit testing on 30 MW sets, and a fair number on 60 MW sets. There was no resulting damage on those sets. One particular set was a weak one, insufficiently supported, and it failed on test. But the test was for that purpose, and it satisfied that purpose; the weakness of the set was found out in the works instead of in the field. The revised machine is what I would consider to be a normally supported machine. Therefore, on a 60 MW set I am quite unequivocal in saying that there should be a 100% test.

With the 180 MW machine, one has to think a little harder. One can alter the voltage and swing the reactance, as Mr. James suggested, but I still think that we shall have about twice the current that we have in the 60 MW set, and if we have twice the current we have four times the mechanical forces. If we are to

be asked to accept a simple extrapolation up to the range of four times our present experience, I could never agree.

The design of the machine, as with most electrical apparatus, is based on experience and practical investigation at the works and on tests. The authors make some play of the fact that one may not get more than 50% short-circuits in general because of the step-up transformer. That is quite true; but one still gets faults, and if the authors suggest that they can produce a completely fault-proof machine, I do not believe them. There are possible machine faults: i.e. there are the hydrogen seals, there are the bare copper connections and there are the main-transformer and the unit-transformer windings subject to fault. Only a few months ago we had a unit-transformer fault and, as a result, the machine, an elderly one, flashed over. There was a single-phase flash-over which became a 3-phase fault, and it was necessary to have a complete rewinding. We cannot dismiss these things.

When we are stepping into the dark, as with 180 MW machines, we must know that the thing is safe to begin with, and we must know that it will not wreck itself and perhaps somebody else when it faults. We must know that when we get a fault we are not going to have that machine out of use for six months.

Mr. Kilner made a case against himself when he said that the model test does not reproduce the actual winding. Of course it does not. These alternators are mostly hand-work, and we must have proof that the work is done properly. One cannot carry out a test on a nice model and say that it will be just as well in an actual machine. A test at 50%, which is a quarter of the possible forces, does not give us anything; we must have something higher than that.

I do not know what designers are running away from. There is a straightforward problem. The forces are going up four times. Surely development and design work must be carried out on which to base the designs. If first that development and design work is done, I think it would be reasonable to accept 75% routine tests. We must have something more than a quarter of the forces to check workmanship alone and to check that the designs are in fact repeated. I would be willing to agree to 75% tests with a background of proof. If you cannot give that proof, then have 100% type tests and 75% routine tests.

Mr. W. J. Carfrae: I think that it will be agreed that the margin of mechanical strength on end-windings is none too great. I doubt very much whether any manufacturer would be prepared, at the present time, to guarantee a machine against damage in the event of out-of-phase synchronizing as distinct from a short-circuit at the terminals.

I do not altogether agree with the authors that a generator solidly coupled to a transformer will be subjected to smaller forces than when connected direct to a busbar system. Either arrangement can incur a dead short-circuit at the generator terminals. I can recollect an instance where a fall of snow from a roof caused a short-circuit on the low-voltage terminals of the generator transformer, equivalent to a short-circuit on the generator terminals in view of the short length of low-voltage connections.

My view is that machines should be type-tested only. One machine, preferably the first, of any batch should be subjected to a sudden short-circuit test at full voltage, but the remainder should not be subjected to any sudden short-circuit tests, save possibly at a voltage substantially below normal to check reactances. The purchaser might, as a result of this type test, have one machine weaker than the rest, but unfortunately, as a previous speaker has pointed out, this cannot be determined by inspection.

From various small indications over the years I feel quite convinced that neither repeated sudden short-circuit tests nor repeated high-voltage tests are beneficial to windings in the long run, and I suggest that some discretion should be used in specifying tests of this nature.

I agree entirely with a previous speaker that analytical methods will never tell us in advance how an end-winding will behave under sudden short-circuit conditions, but calculations of this type are of value in giving a picture of the forces existing.

I feel that replica windings as described by the authors are not a generally practicable proposition. For a piece of special research work such as is described in the paper a replica is probably fully justified. Where, however, a limited number of generators of any one design are built, as is generally the case with the type discussed in the paper, the cost of replicas would be excessive. I imagine that the cost of a replica as described in the paper would be a substantial fraction of the cost of a full-size stator. Furthermore, as one previous speaker pointed out, satisfactory performance on the replica is no absolute guarantee that the production machines will all be equally good.

I take it that the replica was wound for the same voltage as the original machine, but would be pleased if the authors would confirm this.

Mr. W. D. Horsley: It has long been known that the forces in turbo-alternator windings are high and the investigation adds considerably to our knowledge of this problem although the authors rightly come to the conclusion that the movement of coils and consequent damage to the insulation is almost impossible to evaluate. In addition to the complexity of the forces there are many variable factors which include methods of bracing the coils, the nature and application, and the treatment of the insulation.

It is generally accepted that alternator windings should be designed and built to be capable of withstanding a sudden short-circuit at full voltage, although it may be argued that a test is onerous and should not be made. Furthermore, the occurrence of such a fault is very infrequent and there are therefore some grounds for considering whether proving tests at full voltage should be specified as routine procedure.

Nevertheless, modern alternators are normally capable of withstanding a full-voltage short-circuit test without damage to the windings. In the past many alternators have been short-circuited at full voltage, sometimes repeatedly, to obtain test data, and subsequent operation has proved that deterioration has not occurred.

Since the forces vary as the square of the short-circuit current, the reactance of the alternator—which primarily determines its value—is of first importance. The natural inherent reactance of an average design is in the range 10–12½%, and, if required, may be raised to, say, 15% by increasing the size of the stator core—and, incidentally, the cost of the alternator. The higher values may be greater than required to safeguard the windings, but may be necessary to reduce the short-circuit power of the system.

As stated by the authors the problem of designing an alternator to withstand full-voltage short-circuit tests becomes increasingly difficult as the output of individual units is increased. On the other hand, the use of hydrogen for cooling, the adoption of higher gas pressures and the development of direct-cooled windings all tend to increase the specific output and, therefore, the natural inherent reactance.

The problem of transport becomes more difficult as the size of individual units is increased, but by taking advantage of these design features a reasonable value of reactance may be obtained.

The short-circuit current (3-phase, r.m.s. value) at full voltage for the alternator discussed in the paper is given as 47 kA, which corresponds to a reactance of about 6%. This value is unusually low, and the difficulty of bracing the windings to withstand a sudden full-voltage short-circuit is correspondingly great—but as shown by the authors it is not unsurmountable.

End-windings of both the basket and the involute types have been satisfactorily designed and constructed for short-circuit-testing generators having a reactance as low as 3%.

The projection of the conductors at the ends of the core is particularly vulnerable, and it is essential that the main conductor insulation should have some degree of flexibility.

It is stated in the paper that elastic deformation occurred up to currents corresponding to 50% voltage. Was this current 50% of the 100% voltage, or less owing to the higher reactance at lower current values? In either case it seems that with a reactance of 12½% permanent deformation would not be caused by a short-circuit at full voltage.

Proving the stator windings is not the only object of making short-circuits; the determination of the actual value of reactance is also important.

Owing to saturation the short-circuit current is not proportioned to the voltage, and an accurate value can be determined only by a full-voltage short-circuit on the alternator itself. A replica of the windings would not be suitable for this purpose.

It may therefore be generally agreed that a short-circuit test should be applied to selected machines, although the voltage at which it is applied may be open to argument.

If it is established that synchronizing an alternator transformer unit 180° out of phase is equivalent to a direct short-circuit at 80% voltage, then the test voltage should be not less than this figure.

The possibility of a fault developing between the alternator and transformer primary windings, although unlikely, cannot be excluded. Such a fault may occur at full load when the internal generated voltage in the alternator is about 10% higher than normal, and even if the arc resistance is taken into account, the fault current may be as high as that due to a direct short-circuit at full voltage.

Taking all these factors into consideration it seems not unreasonable to make a type test on one alternator at 100% voltage and to apply a 50% voltage test on others of the same design.

Mr. J. W. Laing: I have always been of the opinion that we ought to be able to build machines which will stand sudden short-circuits. Alternators for switchgear testing have been in operation for about twenty years with reactances of the order of 2½%. Special precautions were taken to meet the resulting heavy forces and the machines have survived for very many years.

I think what is bothering us more than anything else is the rapid increase in rated output of machines. Normally we would expect a reduction in reactance with consequent greater stresses on short-circuit, but with better cooling methods it should be possible to maintain reasonable values of reactances so that the problem of bracing windings is not greatly removed from existing practice. We ought to be able to brace the windings so that we stop them from moving and still maintain adequate ventilation. In my opinion, this can be done provided that the insulation on the conductors is properly compacted and finished to close tolerances. If this provision is met, adequate bracing at the most vulnerable position—where the conductors leave the core—can be provided. Adequate bracing of the remainder of the end-winding can be effected only by experience built up from testing of machines. I would mention that the machines from which experience has been gained were, in many cases, subjected to several full-voltage short-circuit tests and have shown no deterioration over many years.

Mr. J. F. Dunn: Having been responsible for witnessing a number of short-circuit tests on medium- and fairly large-capacity alternators from time to time over a number of years, I find that I have a good deal of sympathy with some of the proposals put forward in the paper.

Concerning the results of the tests quoted in Section 3.1, I have heard and seen enough at this meeting to suggest to me that, although no actual failure has ever occurred during testing or afterwards in any of the machines with which I have been associated, the possibility of the end-winding insulation being impaired must nevertheless have been there in some cases—particularly when, as has happened once or twice, there has been visual evidence after the tests of slight movement of end-windings having taken place. With the considerably increasing forces which apply as machines become larger and larger, it therefore seems that some change in testing technique may well become necessary. Although I am entirely in agreement with some of the earlier speakers to the effect that no reduction in the severity of the tests should be contemplated—indeed the larger the unit the greater the safety margin surely ought to be—nevertheless I think that the paper gives a strong lead in other respects.

With regard to the form of test which ought to be applied I must say that I tend to agree with the authors' suggestion that type-testing is a more satisfactory approach than the routine testing of machines which are then put into service. The point is, however, that the resulting reduced safety margin may not be evident without dismantling and carefully examining the windings, and I would feel very nervous about operating a machine which had been subjected to end-winding movement like that which the authors described in presenting the paper.

As indicated in the paper, type testing can be approached in two ways, namely (*a*) to adopt a replica test arrangement on the lines illustrated, and (*b*) to put sample windings on one of the machines which is actually going into service and then strip these off again after the application of the short-circuit and high-voltage tests. It is evident that in either case a high-speed photographic recording of the test is desirable, and, furthermore, that the subsequent stripping down after the high-voltage tests should be carried out under close supervision by experienced observers—much as has been standard practice for many years with considerable advantage following bending tests on high-voltage cable during sample testing at manufacturers' works (in accordance with B.S. 480 and with British Electricity Authority and other cable specifications).

Whether replica or full-stator type-testing (or either) is eventually adopted will no doubt depend upon economic aspects as well as upon technical and other points of view. Perhaps the authors can give us some idea of the relative cost of these two approaches—but I would seriously suggest that unless it can always be shown to customers' engineers, or to independent consulting engineers acting on their behalf, that in each case tests made on a replica really are representative of similar type tests made on an actual alternator, the latter would naturally tend to give more confidence than the former. The authors themselves outline these difficulties and express doubts in this connection in Sections 2.2 and 4 of the paper, and although in their Conclusions and Recommendations they evidently look upon routine testing with disfavour—and yet in the same paragraph refer to the high cost of manufacture and testing of a replica—they nevertheless do not discuss or compare the relative cost of this with testing a fully-wound stator and then dismantling and re-winding it for service as suggested above.

Mr. M. Waters: In the end-windings described short-circuit forces not only stress the copper well past its elastic limit but also bruise the insulation, and the movement of the conductors is such as to exclude any possibility of calculating the mechanical stresses. Design must be by rule of thumb, and short-circuit tests are necessary to prove every winding.

I suggest that a construction should be sought in which the conductors are rigidly held at a sufficient number of points to enable the stresses in the copper and insulation to be calculated. This might require a radical change in the methods of supporting

the conductors, but if it could be successfully carried out it would eventually eliminate the necessity for short-circuit tests except perhaps as type tests.

Mr. N. G. McCullagh: Mr. James mentioned that we must bear in mind when testing new alternators, that they should have a long life, during which time deterioration will occur in the various insulation materials of the machine. I think the point was very well made, and it emphasizes the fact that we must do everything we can to reduce deterioration of the winding supports, and in the insulation itself.

Mr. Winfield spoke of the use of string and wood in the end-windings of machines. I think that he was perhaps really expressing the view that the end-winding support system is not susceptible to exact calculation. In fact, the materials at our command have improved. We now have available glass cord instead of string; glass is a more reliable material with known properties and it suffers less from deterioration. We also have materials which are far superior to natural wood for the support brackets themselves, materials whose properties are known and which do allow us to make a more definite attempt at calculating the behaviour of the support structure.

Another speaker asked whether different support construction was used to provide very rigid support for the straight portion of the coil outside the slot. I think that within the limitations of the ventilation requirements of the machine a great deal can be done at that point, and also the bracket system outside, which supports the evolute, can be redesigned within the limits of the ventilation requirements to give a more rigid and permanent structure which will not suffer from deformation or from looseness in after-life.

I feel that the alternator is changing in regard to the materials and the amount of design attention given to the end-winding supports. I am sure these improvements will enable us to provide end-winding supports of sufficient strength and stability on the larger alternators which are coming into use in the near future.

Prof. M. G. Say: The basic expression is eqn. (2). Eqn. (1) is largely irrelevant, and in any case is given in units that could hardly be more heterogeneous. A fundamental expression should be in a single consistent system of units.

Unlike other speakers, I think that the authors' analysis is of considerable value, not only as estimating the magnitudes of the forces, but even more their directions. This should make it possible to attack the bracing problem anew, as may be urgently necessary when 200 MW machines are called for.

Would it be possible to open out the slot ends for the last few centimetres to avoid the sharp transition from the well-supported slot-conductor to the much weaker end-conductor? In a tele-communication phrase, the slot and end portions would be better "matched."

Would a designer without 50 years of works practice behind him tackle this problem in the present fashion? Perhaps an end construction in which the conductors are clamped into shallow slots cut into solid insulating cones might be possible if the ventilation could be well arranged. Some method not relying on small blocks tied in with string seems essential.

Prof. C. E. Moorhouse (*United States; communicated*): It is to be hoped not only that the authors will be able to carry out further investigations with the "replica" described, but also that this combination of design and experiment will become much more common than has previously been the case.

Tests carried out with the replica under steady-state conditions also could be of considerable value in establishing more rational expressions for the computation of the end-turn leakage reactance of the stator windings. It is not surprising when one considers the mathematical difficulties inherent in the complexity of the configuration that no really valid expression for this quantity has been derived, but it is disconcerting to find that little or no experiment, as distinct from estimation guided by the apparent results of tests on actual machines (usually performed for other purposes), has yet been carried out on a useful scale.

One is led to wonder why the second displacements [curves (*a*), (*b*), (*c*) of Fig. 6] are greater than the first ones, when presumably the actual currents flowing are somewhat less.

Do the authors consider that these displacements are larger because the constraints are less—slackness in bindings—or have the coefficients in the force expressions changed because there is a new configuration of the coils, since some of the displacements appear comparatively large. Could further useful information on this point be obtained by the use of strain gauges on suitable portions of the actual windings or on spacers located between the coils?

Is the "positive" direction of the circumferential displacements to be interpreted as the direction of rotation of the rotor?

[The authors' reply to the above discussion will be found on page 119.]

NORTH STAFFORDSHIRE SUB-CENTRE, AT STAFFORD, 22ND NOVEMBER, 1954

Mr. W. D. Worthy: The ageing of machine windings must be due partly to chemical deterioration of the insulating materials and partly to the cumulative effect of stress reversals caused by electromagnetic forces, thermal effects and vibration. As with fatigue in metals, it is probably true that the ageing effect produced by stress cycles increases very rapidly with the magnitude of the applied stress. The few cycles of excessive strain imposed during the short-circuit overloading may contribute as much to the ageing of the insulation as all the electro-mechanical and thermal stresses imposed in several years of normal running.

Any measures taken to avoid the imposition of large strains must surely increase the expectancy of life of a machine.

The measurements and analysis of the stresses and distortions produced in the windings of this alternator and the model have been very illuminating. The writhings of the conductors shown on the high-speed cinematograph film provide striking confirmation of the need for the attention that has been given in the paper.

I was surprised to observe the very large oscillatory displacements of the end-windings in the region close to the stator slots. Is it not possible to include more blocks and strapping in this critical position to distribute the forces and relieve the pressure on the conductors where they enter the slots?

Mr. R. G. Hill: I think the authors have shown very convincingly that application of an instantaneous 3-phase short-circuit to a turbo-alternator from 100% normal voltage is unnecessarily severe. It seems to me that two issues are involved —first, some test is necessary to prove the design of the bracing of the stator overhang, and secondly, some test is necessary to prove that the workmanship in the bracing is up to standard.

Do the authors consider it necessary to build a replica, similar to that described in the paper, to test the design of the bracing in each case? I wonder also whether they would care to comment on the idea of short-circuit tests below normal voltage to prove the workmanship, and how they would decide what value of voltage should be used for this test.

Mr. D. K. Arkwright: Before asking for a relaxation of the short-circuit test, we should perhaps remember that the test from

full voltage on open-circuit may already represent a relaxation from the worst possible service condition, when the machine is short-circuited on load. The internal e.m.f. of the machine is then greater than its rated terminal voltage, and the initial short-circuit current and force are correspondingly higher.

I would, however, suggest an alternative approach. The authors have shown that a direct short-circuit is not now likely in practice. Nevertheless, it remains a possibility. On the other hand, there seems not even the possibility of a machine in service having to withstand a voltage corresponding to its high-voltage test. It would therefore be more logical to carry out the normal short-circuit test, at customer's request; but, since the machine windings after the test cannot be regarded as being in a new condition, to reduce the subsequent high-voltage test.

Mr. E. Bolton: Have the authors any information on the effect of a large number of smaller short-circuits on the insulation at the overhang, which is the more usual case in service?

Is it possible that the repeated flexing of the insulation will lead eventually to breakdown, even though the conductors do not show permanent deformation? Is there any evidence from machines which have broken down in service that faults have occurred from this cause?

I would be interested to hear whether the authors feel that any of the more recent developments in insulating materials would be more suitable for the end-windings where the relative brittleness of the conventional mica insulation exaggerates the seriousness of coil movement.

[The authors' reply to the above discussion will be found on page 119.]

NORTH-EASTERN CENTRE, NEWCASTLE UPON TYNE, 13TH DECEMBER, 1954

Mr. P. Richardson: In an effort to bring home the nature of the problem discussed by the authors, it might be as well to point out that a 200 MW 0·8-power-factor generator having a reactance of $12\frac{1}{2}\%$ will deliver a fault power of 2 000 000 kVA. This is very similar to the output which is obtained from switchgear-testing generators, and at first sight it appears that there are strong grounds for recommending that the severity of the sudden short-circuits applied to generators, particularly those of larger output, should be reduced so as to avoid damage.

While it is agreed that the more obvious signs of movement are to be observed in the end-windings of a generator, it should be realized that the forces on the conductors within the slot are fairly severe. As pointed out by the authors, where the slot contains coil sides of different phases, there is a repulsive force tending to drive the top conductor into the air-gap. Where the conductors in the slot are of similar phase there is a force towards the bottom of the slot and this cannot be discounted. I have seen a cross-section through the bottom slot, built up with conductors removed from a short-circuit testing generator built in about 1929, in which the conductors in the slot were of a similar phase. It was apparent that the constant hammering of the conductors towards the bottom of the slot had damaged the slot insulation. It is, however, well known that when Micanite is bent through 90°, cracks are likely to form, and later designs were modified to avoid such distortion of insulation. The commercial type of turbo-alternator, however, is of somewhat different construction, in that the conductor consists of a series of thinner strips each of which is insulated to minimize eddy-current losses, and careful bonding and insulation of such conductors is necessary to avoid impact damage under fault conditions.

The experience gained on a series of short-circuits on the 60 MW 60 c/s machine for Canada is most instructive. If I am correct in my assumptions that the test circuit was set at 47 kA to represent a full-voltage short-circuit condition, the reactance of the generator was only just over 6% at full voltage. Tests on the experimental stator indicated that up to currents equivalent to a half-voltage short-circuit, the deformations were elastic, there being no permanent deformation, and it seems that had the generator been designed with a reactance of the order of $12\frac{1}{2}\%$ difficulties would not have ensued. It is interesting that the damage to conductors occurred at the end of the stator core owing to circumferentially directed forces. Would the authors say whether the faults were more or less uniformly distributed on either side of the conductors or whether they indicated that the circumferential displacement had been in a similar sense in each case?

The position of the faults and the nature of the movement observed lead one to ask whether the alternator could not have been designed so as to be capable of withstanding the sudden short-circuit test. As the authors will no doubt be aware, I am a supporter of the insulation known as flexible, in which the mica flakes constituting the conductor insulation are bonded with a non-drying varnish which retains quite a large degree of flexibility as opposed to varnishes which are comparatively hard and brittle at the temperature normally obtaining when a sudden short-circuit test is carried out. In addition I consider it to be good practice to insert an insulating sleeve around the conductor where it passes through the end sections so as to reduce the rate at which the mechanical support of the conductor changes from the iron of the slot to whatever is provided in the end-windings.

The circumferential displacement of the knuckles is proportional to the forces applied; it also depends upon the strength of the conductor. If, for example, the conductors were built up with pairs of strips lying side by side, instead of with a single strip of twice the width, then the moment of resistance would be only one-quarter of that of the full strip; this, of course, presupposes that the bond between pairs of strips lying side by side is negligible, and I doubt whether it is practicable to make a very effective bond.

I have seen photographs which illustrate the movements which have been observed in the end-windings of alternators, made in the United Kingdom, under fault conditions. The background of this fault is rather important in that a flashover in the end-windings occurred on a machine which was situated in Canada, and the resulting carbonization due to fire and arcing necessitated stripping of the end-windings at the exciter end only. In order to save time the purchaser arranged to have the end-windings re-insulated and replaced by a firm of electrical engineers in Canada, but shortly after recommissioning a similar fault again occurred in the end-windings of the exciter end. The photographs showed the nature of the distortion observed in the end-windings after the second fault. No movement of the end-windings had occurred in the end-windings of the exciter end. The photographs showed the nature of the distortion in the end]windings applied to the end connections, together with a failure to ensure adequate radial packing.

The winding used in this machine was a standard type of winding used for many years and it had a naturally high reactance. With the advent of hydrogen cooling and the higher ratings associated with such machines, the form of construction was changed to a winding similar to that illustrated in the paper. It was realized that the reactance of such a winding tended to be less than that of the previous type of machine and arrangements were therefore made to incorporate some additional length in the reactance slot, so as to maintain a satisfactory value of reactance.

One consequence of this was that the stator weights were appreciably higher than could have been offered if a lower reactance had been considered acceptable by the designer. The first of a number of 60 MW hydrogen-cooled generators was subjected to a full set of short-circuit tests without any apparent movement. It should be explained here that the end-windings of all these alternators were completely impregnated, so that, in addition to providing a more effective bond between the conductors and their packing, it incidentally left a continuous varnish film over the surfaces of the end-windings so that movement sufficient to open up the varnish film was readily detectable.

I agree that the arguments put forward by the authors relating to the reduction of fault current due to arc resistance are reasonable. On the other hand, it was only recently that in Scotland a circuit-breaker was closed in a power station when the earthing bar was still in position. During the 1939–45 War barrage balloons had a habit of drifting across the overhead lines. We have had generators synchronized 180° out of phase on the busbars—without, incidentally, resulting in a rewind—so the possibilities of a direct fault without the modifying effect of the arc resistance seem to be present.

It may be of interest to refer to a switchgear-testing generator manufactured in the United States in which the end-windings are similar to those in Fig. 5, except that they are arranged axially instead of at an angle to the axis. These windings are actually bolted to a non-magnetic steel plate fitted around the back of the end-winding. The short-circuit output is 1·62 MVA at 15·5 kV and the winding insulation is equivalent to a 26·5 kV 3-phase machine. While it is agreed that the provision of adequate ventilation to ensure a continuous rating would present a problem, it does show what can be done.

It appears logical to limit the short-circuit test voltage where the alternator is connected direct to a generator transformer, as will be the case on most of the large units. However, where there is no generator transformer between the generator and the busbars, I still feel that a full short-circuit test is justified. Short-circuit tests may be regarded as a yardstick of manufacture, somewhat similar to high-voltage tests, and whatever may be agreed in the way of reducing test conditions, the designer must continue in his efforts to produce a generator which is capable of withstanding a full-voltage short-circuit.

Mr. D. J. Marsh: The authors state that in modern installations of the unit-construction type, short lengths of busbars or cables are used to the step-up transformers, and the likelihood of faults occurring near the machine terminals is more remote than under the conditions obtaining when B.S. 225 was originally prepared. This, of course, is true, but we must not neglect these possible faults and should ensure that machines are capable of withstanding them without damage.

It has also been stated that rigid bracing of end-windings becomes increasingly difficult as the rating and consequent overhang winding-lengths increase. This is true only in machines using small-angle involute windings. It is not true where the concentric or 90° involute type of end-winding is employed, since these can be clamped, with no extra difficulty, to the core end-plates with insulated non-magnetic steel studs.

On the question of the magnetic fields in end-windings from which short-circuit forces result, it may be argued that the strength of these fields could be further reduced by the use of additional non-magnetic materials. However, this would have the effect of decreasing the end reactance, thereby, of course, increasing the fault currents and resulting short-circuit forces.

An increase in the quantity of magnetic material in the end-windings would reduce fault currents but increase the stray losses. As stray losses are present under normal service conditions it is the designers' primary duty to keep these low and thus to produce machines which have a high efficiency under normal healthy service conditions. Perhaps one day our successors will arrange to fit special "reactance-increasing attachments" just prior to the occurrence of fault conditions.

I am surprised to learn that sufficient end-winding movement took place during a 75%-rated-voltage sudden 3-phase short-circuit to cause insulation breakdown on the standard 60 MW machine mentioned by the authors. Perhaps I have been very fortunate in that, of the many large alternators I have seen subjected to repeated 100%-rated-voltage sudden 3-phase short-circuits, the subsequent voltage tests to B.S. 225 have been satisfactory.

Perhaps the authors would be good enough to give us some actual figures of the forces in magnitude and direction under various fault conditions. It is to be hoped that they will regard this only as an interim report and will go on from strength to strength in their researches into this subject. It is a subject which at present defies exact analysis, and is confirmation that the prediction of performance of turbo-alternators is not yet a mathematical science but rather a satisfying and creative art.

Mr. P. Olsen: Up to the present time the design of end-winding supports appears to have been, owing to the complexity of analytical treatment, based on trial and error. In other words, a sudden short-circuit test was applied to a machine, the windings were examined for movement and electrical voltage tests were applied to see if the insulation had been damaged. This method of approach has been quite satisfactory, but of course it is very necessary to cater for changing conditions and it is as well to review the methods which have hitherto been accepted.

The analytical treatment outlined in the paper forms a useful basis even for this difficult problem, and the evidence which the authors have put forward will enable machine designers to have a clearer picture of what is required. It appears that the start of the authors' investigations occurred at a time when difficulties were being encountered as detailed in Section 3.1, and it would be interesting if the authors could state the comparative peak-current values of the particular machine in question compared with machines previously built. It is possible that there may have been some complacency in this case and that failure to realize the new conditions has given rise to the difficulties. It would have been interesting to have details of the bracing employed originally on the machine in question and to know whether these were specially designed or whether normal methods were applied. It is noted that considerable modification was made to the end-winding supports and it was presumed that this was done without appreciably affecting the ventilation of the end-windings. It therefore appears that the bracing was inadequate in the first place and had not been proved.

It is felt that the function of the model tests should be to prove new designs of end-winding support and packing arrangements, but this should not preclude type tests on the actual machine. The model tests, according to the authors, are more rigorous than a test on a machine, but it would be interesting to know whether the overturning moment on the model has been measured at any stage. One feels that the absence of the field system does not produce the interacting forces which tend to twist the machine stator with the resulting pressure on the side of the slot exerted by the conductors. If the model tests produce greater forces on the end-windings than a machine test, one would have thought that the number of faults produced on a model would have been at least equal to those produced during the machine test. The authors state quite definitely, however, that the model successfully withstood the pressure tests even after a considerable number of tests were carried out.

Sudden short-circuit tests at full voltage have not, so far as is known, been responsible for insulation breakdown in service,

and there must be a fairly large number of machines which have undergone the tests which the authors consider are too rigorous, but which are still quite sound after many years of operation. On the other hand, full-voltage short-circuit tests have shown up constructional weakness not directly related to the particular design of bracing. One such case was that of a machine where the scarf joints in the insulation had not been properly made, and it is felt that had the two sudden short-circuit tests not been applied, this would have gone undetected and, doubtless, the fault would have shown up at a later stage. It should be borne in mind that the windings of large machines can be subject to vibrations which, while not appearing to be severe, can unsettle the supports, the packing and the insulation itself.

Mr. D. Riach: It seems to be regarded that a 3-phase short-circuit at the turbo-alternator terminals, with 100% voltage, is the most severe short-circuit that the turbo-alternator might ever have to withstand in service. This, however, disregards the fact that in actual service the voltage could rise to as much as 150% of normal if the load were thrown off with the excitation on manual instead of automatic control. I suggest that the short-circuit tests at the works should be at 125% of normal voltage in order to obtain a more adequate appraisal of the mechanical and electrical strength of the windings.

Mr. D. F. Davidson: The authors suggest that it is becoming more difficult to brace the end-windings of the very large alternators without severely interfering with the flow of cooling gas between the coil ends. This is certainly true for conventional designs. When cooling is carried out by circulating the coolant at a high pressure through passages inside the conductors, which is a feature of the latest American designs, this limitation does not arise, and it is possible to incorporate additional packing blocks to obtain a very solid end-winding structure. Another advantageous feature of the designs with inner cooling is the inherently high reactance obtainable with increased electric loading.

The coil numbers corresponding to the line and neutral ends of each phase are not marked on Fig. 4. Were the coils which broke down after the short-circuit test near the line terminals? Was there any indication that running for several hours on open-circuit above normal voltage had caused further deterioration in already weakened insulation?

The authors emphasize the important fact that the magnitude of any short-circuit currents in practice will be less than those resulting from a solid short-circuit at the machine terminals. Their proposal that the works test should consist of a flash-over initiated by fuses appears rather alarming. The authors' comments on their method of applying this test and the consistency of the results would be appreciated.

Some details of the movement-recording devices used during the test programme would also be of interest.

THE AUTHORS' REPLY TO THE ABOVE DISCUSSIONS

Messrs. J. B. Young and **D. H. Tompsett** (*in reply*): Many contributors to the discussion have referred to the extremely good record of alternator performance in withstanding full-voltage short-circuits and subsequent high-voltage tests. This confirms our own experience and indicates that machines generally have been designed with adequate mechanical margins. Most representatives of turbo-alternator manufacturers have agreed with our view that full-voltage short-circuit tests nevertheless cannot fail to have some detrimental effects on the insulation.

On the other hand, in supporting the practice of carrying out such tests, Mr. James and Mr. Olsen maintain that there is no correlation between machines on which short-circuit tests have been applied and the incidence of failures of generators during their operational life. Because of the relatively small number of faults which could, in any case, be attributed to the results of such tests, a large number of records would have to be available before the conclusion quoted above could be considered statistically sound. Even if this correlation is only small, the increased probability of a forced plant outage, with its attendant expense, must be set against the hypothetical value of the test.

Mr. James is frank in his admission that he may be biased in his views on short-circuit testing because of his early training on smaller machines. Many purchasers may have similar feelings, and it is chiefly to these that we wish to appeal for reconsideration of their attitude. Several speakers appear to have an entirely wrong impression of our recommendations; Mr. James refers to a reduced factor of safety on the windings, but as stated in Section 7, it is not intended that any relaxation in bracing effort should be permitted. The machines would still be designed to withstand the assessed forces corresponding to a solid 3-phase short-circuit from full voltage, but our contention is that such a severe test should not deliberately be applied to the windings.

Mr. James mentions that American practice is not to specify short-circuit tests on production machines, and it is fair to say that from the point of view of coping with short-circuits in service, an alternator which has not been deliberately short-circuited would in fact have an increased factor of safety. Our recommendation therefore agrees with long-established American practice. We feel sure that if Mr. James examined the end-winding bracings on alternators of American manufacture he would agree that they are not mechanically superior to those constructed in this country; yet presumably they give satisfactory service. We understand that the special American machine described by Mr. Richardson has a 4-pole stator winding in which the problem of bracing is less severe.

We do not deny that terminal flashovers can occur, but proper control and design of the busbars, etc., at generator voltage should minimize this possibility—particularly such incidents as those mentioned by Mr. Carfrae and Mr. Richardson, or the circumstances envisaged by Mr. Riach. We agree with Mr. Horsley and Mr. Arkwright that, whatever the nature of the fault, the forces will be slightly greater on a loaded machine at a given voltage than on an unloaded machine, since the relevant internal voltage of a loaded machine will be slightly higher than on open-circuit.

Reference has been made by Mr. Horsley and Mr. Hill to the necessity for proving the general manufacturing standard of any machine, and with these views we are in full accord. It is our belief that this can be satisfactorily demonstrated by a short-circuit test at less than full voltage, coupled with a thorough inspection of the workmanship involved.

We do not agree with Mr. Winfield in his assumption that the short-circuit forces on 180 MW and 60 MW alternators will be in the ratio of four to one. As Mr. Horsley and Mr. Davidson remark, owing to the higher electrical loading on "inner-cooled" machines, the percentage subtransient reactance will be appreciably higher than in conventionally cooled designs. In fact, the forces on the first 200 MW alternator to be ordered in this country are estimated to be approximately 90% of those in a 100 MW machine, for which a replica stator has already been constructed and successfully tested; no difficulty should therefore be encountered in this respect on these larger machines, particularly as the ventilation conditions permit more solid blocking of the end-windings.

The subtransient reactance of the 60 MW alternator referred to in the paper is unusually low; the normal expedients for

increasing reactance could not be applied on account of weight and dimensional shipping limitations. Further, the actual reactance was lower than that expected, with a resultant increase in the short-circuit forces. In spite of this, the records described in Section 3.1 indicate that very little visual evidence of damage was apparent following the short-circuit tests.

A number of speakers refer to the value or otherwise of the analytical work which forms part of the investigations reported in the paper. The distribution of the end-winding forces is amenable to approximate calculation but, as stated in Section 2.2, no attempt was made to evaluate precisely the resultant conductor movement and the damage to the insulation. This information on the forces, together with results obtained on the replica, enables tests to be performed on individual coil samples without the expense of constructing further complete replicas. We should be interested to know what other approach to the problem Mr. Winfield has in mind in the design and development work which he rightly advocates. He and other speakers criticize the replica as probably not being representative of the workmanship in a production machine. Every effort was made during its manufacture to minimize any differences in this respect; the original decision to construct a full-size representation, and not a "model," was to validate comparisons between the replica and the actual machine. The same sort of comparison exists between individual alternators where the practice is adopted of short-circuiting only one machine of an identical series.

There are a number of specific inquiries relating to the replica and the tests carried out on it. In reply to Mr. Kilner we believe that the method of attaching the conductors to the supporting structure was as great an improvement as that effected in the structure itself. A construction which effectively constrains the outer layer of winding in both the radial and circumferential directions is a primary requirement; the inner layer must then be fixed in position as rigidly as possible. Mr. Kilner's observations and illustrations are of interest in this connection, but it appears that the bracing method shown would be more effective in constraining radial rather than circumferential forces. We should be interested to see a film of winding movement with this type of bracing. We do not believe there are significant differences between the maximum forces on the two layers, but the difference in constraints may lead to greater movements on one than on the other in particular cases.

Mr. Kilner makes a valid point in drawing attention to the temperature of the windings at which a short-circuit test should be carried out; we wonder whether those who favour such tests would even object to the windings being warm on the grounds that a machine in service might only just have been put on load when experiencing a fault.

We confirm that Mr. Carfrae is correct in thinking that the replica conductors were insulated precisely as those in the alternator. He and Mr. Dunn raise queries about the relative cost of a replica for end-winding tests. Our experience indicates that the cost of constructing a replica is of the order of 10% of that for the complete alternator, while to strip and rewind a stator after a short-circuit test, as suggested by Mr. Dunn, would cost about twice this amount.

Mr. Olsen is correct in thinking that the overturning torque on the stator is not reproduced in the replica. However, the forces in the slotted length of the armature core act mainly on the iron surfaces and not on the copper conductors, so that the pressure exerted by the conductors on the side of the slot is not as great as might be imagined. In this connection we agree with Mr. Richardson's remarks that the radial forces in the slots cannot be ignored in the design of turbo alternators. In the end region the field coils lie beneath the retaining ring and change their direction from axial to circumferential as illustrated in Fig. 13(*a*). The effect of the rotor currents is represented in Section 10.2 by the current sheet introduced at radius R_1. Some discussion on the effects of these currents also appears in Reference 1 of the paper.

Regarding Mr. Olsen's point about the relative number of coil-insulation failures in the machine and the replica, it should be recalled that additional strengthening was applied to one end of the latter as described in Section 4.1. A second series of short-circuit tests produced subsequent insulation failures in all three phases.

In reply to Mr. Davidson, the line terminals in the inner layer of winding in Fig. 4 were located at coils 10, 11; 30, 31; 50, 51—there being two paths in parallel through the winding. The original failures in the alternator followed a 100% voltage short-circuit as stated in the paper (not 75% as suggested by Mr Marsh) and occurred at coils 9 and 22 in the inner layer and 6 in the outer layer. The significant point is that all these coils are near the edge of a phase band, 9 being towards the line end and 6 and 22 near the neutral. During the high-voltage tests the line and neutral terminals of each phase were short-circuited so that no particular significance attached to which end the failure occurred. There was no evidence that operation of the machine at above normal voltage had caused insulation deterioration.

We agree with Mr. Horsley that the value of subtransient reactance depends upon the voltage from which the test is carried out. The percentage figures referred to in connection with the replica tests were based on the current obtained in the full-voltage short-circuit on the machine, this being taken as 100%.

Two different types of device were constructed for the purpose of recording the conductor movement, both being actuated through a pivoted arm from a driving bar clamped to the conductor. In one type a small coil was movable in a 2kc/s field produced by four suitably positioned exciting coils supplied from a 2kc/s generator. The instantaneous position of the moving coil in the 2kc/s field determined the 2kc/s voltage induced in it, and this was recorded on a Duddell oscillograph. The other type of device consisted of two sets of parallel plates one of which was moved by the driving arm. The capacitance between the plates was used in an oscillator circuit producing a signal on a Duddell oscillograph which was a measure of the change in capacitance. Both types of unit were calibrated directly using a micrometer head to actuate the driving arm and enabling the oscillograms to be interpreted in terms of the conductor movement.

Prof. Moorhouse raises interesting points in connection with the estimation of end-winding leakage reactance. The calculations and measurements on the magnetic-field distribution provide information towards computing both reactances and stray losses in this region. The comments made by Mr. Marsh in this connection are also of interest. We interpret Fig. 6 as indicating that the bindings are loosened on the first impulse so that on the subsequent cycle the lower force is able to produce a larger deflection. In Section 3.2 it is mentioned that positive deflection in Fig. 4 refers to contra-rotational movement on the inner layer. Mr. Marsh will find that Fig. 4 also gives some indication of the peak circumferential forces; Fig. 3 gives some relationships in terms of the actual conductor currents.

Interesting points are raised by Mr. Worthy in connection with the cumulative effects of cyclic stressing on insulation, and by Mr. Bolton on the question of the effect of the numerous short-circuits of moderate severity which an alternator experiences in service. These are considerations which must be borne in mind in attempting to reconcile the mechanical properties of insulating materials with the performance required to withstand the short-circuit forces.

621.317.39 : 621.165

Paper No. 1622 S
Apr. 1954

SUPERVISORY EQUIPMENT FOR THE INDICATION OF SHAFT DISTORTION IN STEAM TURBINES

By D. ANTRICH, B.Sc.(Eng.), Associate Member, H. W. B. GARDINER, B.Sc.(Eng.), M.I.Mech.E., Member, and R. K. HILTON, B.Sc.(Eng.).

(*The paper was first received* 29*th January, and in revised form* 17*th November*, 1953. *It was published in April*, 1954, *and was read before a Joint Meeting of the* SUPPLY SECTION *and the* STEAM GROUP *of* THE INSTITUTION OF MECHANICAL ENGINEERS 24*th November*, 1954.)

SUMMARY

The paper describes equipment which has been developed to measure the temporary distortions and disturbances which the shaft of a turbine may undergo, particularly during the starting-up period and when sudden changes of load occur during running.

All measurements are made electromagnetically on a disc fitted to the shaft of the high-pressure unit, and are indicated and recorded continuously.

An additional unit has been developed which indicates and records the speed of the turbine, so that shaft disturbances and speed can be correlated easily.

The equipment includes a cathode-ray oscillograph which, when plugged in to the measuring circuits, produces on its screen a trace of the locus of the shaft centre, and permits investigation of abnormal disturbances of the shaft.

Some of the records obtained with the equipment under operating conditions are included in the paper.

(1) INTRODUCTION

Equipment for measuring and continuously recording the temporary distortions which the shaft of a turbine may undergo and the speeds at which they occur has become of increasing importance, owing to the trend towards using larger units working at higher steam temperatures and pressures. The study of such records would enable any progressive deterioration to be detected and permit a subsequent analysis of the machine's performance.

In developing equipment for this purpose it was specified that it should have life and reliability similar to those expected of heavy power-station equipment, and to meet this requirement new principles of design were used which distinguish the equipment from that used by previous investigators in this field.[1,2,3]

Turbine engineers consider that the most important measurements are the axial differential expansion of the shaft with respect to the casing of the high-pressure unit, and the motion of the shaft centre at the end of the high-pressure rotor with respect to the bearing housing. The differential expansion occurs because the rotor, with its smaller weight and heat capacity, changes temperature more quickly than the casing, while the motion of the shaft centre may result from a variety of causes, such as misalignment, instability of the bearing oil-film, or slight temporary distortion (bending) of the high-pressure rotor resulting, for instance, from incorrect barring procedure.

The equipment indicates and records four quantities:

(*a*) The vertical eccentricity at the end of the shaft.
(*b*) The horizontal eccentricity at the end of the shaft.
(*c*) The differential axial movement of the end of the shaft with respect to the casing.
(*d*) Rotational speed of the turbine shaft.

In addition, the equipment indicates the mean position of the shaft journal with respect to the bearing and its oil film, in both vertical and horizontal directions.

Also an auxiliary instrument has been developed, for occasional use during special technical investigations, which displays to an enlarged scale on the screen of a cathode-ray oscillograph a polar diagram of the motion of the end of the shaft.

The paper describes the measurement of temporary distortion of the shaft, the measurement of shaft speed, and gives details of operating experience.

(2) DETECTION OF SHAFT ECCENTRICITY AND DISPLACEMENT

(2.1) Principles of Measurement

A steel disc is fitted coaxially to the part of the shaft which overhangs beyond the outer bearing. Around this disc are disposed three pairs of iron-cored coils or inductors supported from the bearing housing, as shown in Fig. 1. Each pair of coils, e.g. coils AA on the vertical axis, form opposite arms of a bridge circuit, the other two arms being resistors. The vertical component of any movement of the disc with respect to the bearing housing, such as eccentric motion caused by bending of the shaft, will change differentially the air-gaps, and hence the inductances, of the two coils, and thus affect the state of balance of the bridge. Similarly, the bridge which includes coils BB will be sensitive to any horizontal movement of the disc. These two coils are placed slightly below the horizontal axis to enable the shaft to be removed and replaced without disturbing them. Coils CC are placed in front of and behind the disc, and form part of a bridge for measuring axial displacement.

Although it would be possible to supply the bridge circuits from a d.c. source, the resulting readings would be affected by both amplitude of motion and rotational speed, and it would not be easy to separate the effects of these variables. The bridge circuits are therefore excited by high-frequency alternating current. The movement of the shaft causes a modulation of the high-frequency signal that may be conveniently separated to give a reading of eccentricity or displacement that is uninfluenced by the speed of the machine.

(2.2) Circuit Details

Identical circuits are used for detecting the vertical and horizontal components of the radial motion, and Fig. 2(*a*) is a simplified diagram of one of them.

It is necessary for the frequency of the power supply to the circuits to be at least 20 times that of the motion to be measured. Since the eccentric motion is cyclic, of frequency equal to the speed of rotation, and the normal speed is 3 000 r.p.m. or 50 c/s, a power supply with a frequency of approximately 1 000 c/s was chosen, and is fed at 120 volts to the bridge circuits.

To avoid ambiguity of reading the bridge circuits are not balanced, but are biased so that they always work on one side

The paper is a communication from the Staff of the Research Laboratories of The General Electric Company, Limited, Wembley, England.

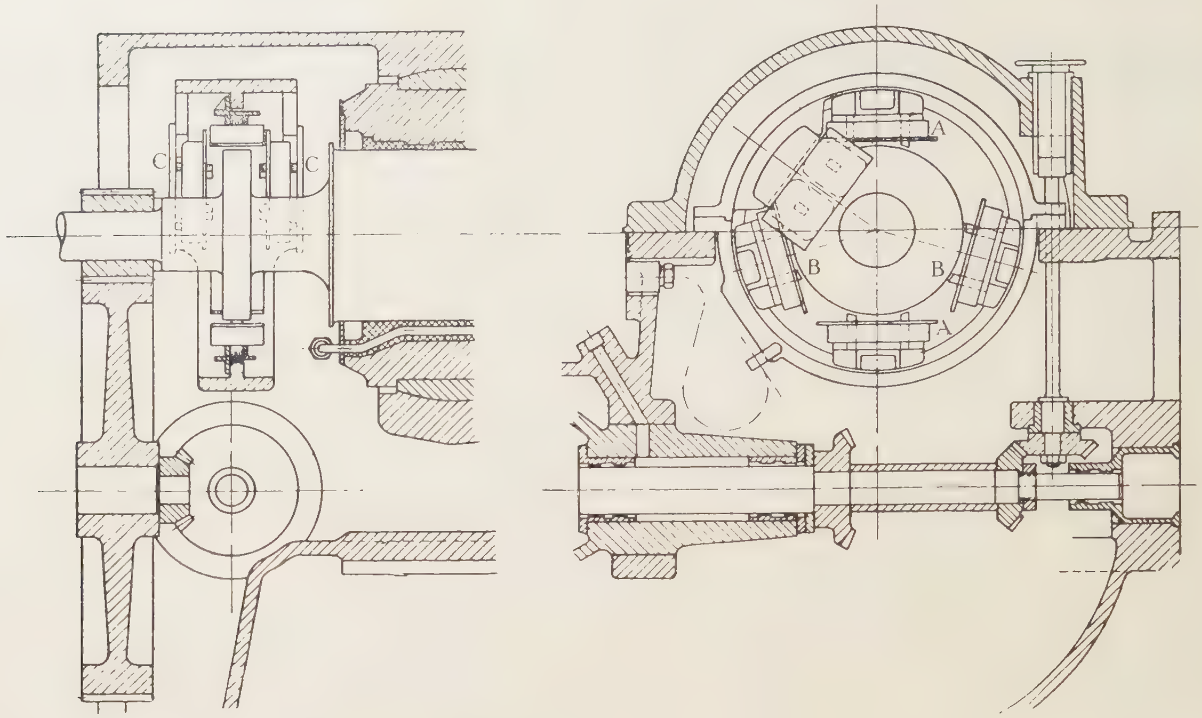


Fig. 1.—Position of the detector coils on the turbine.

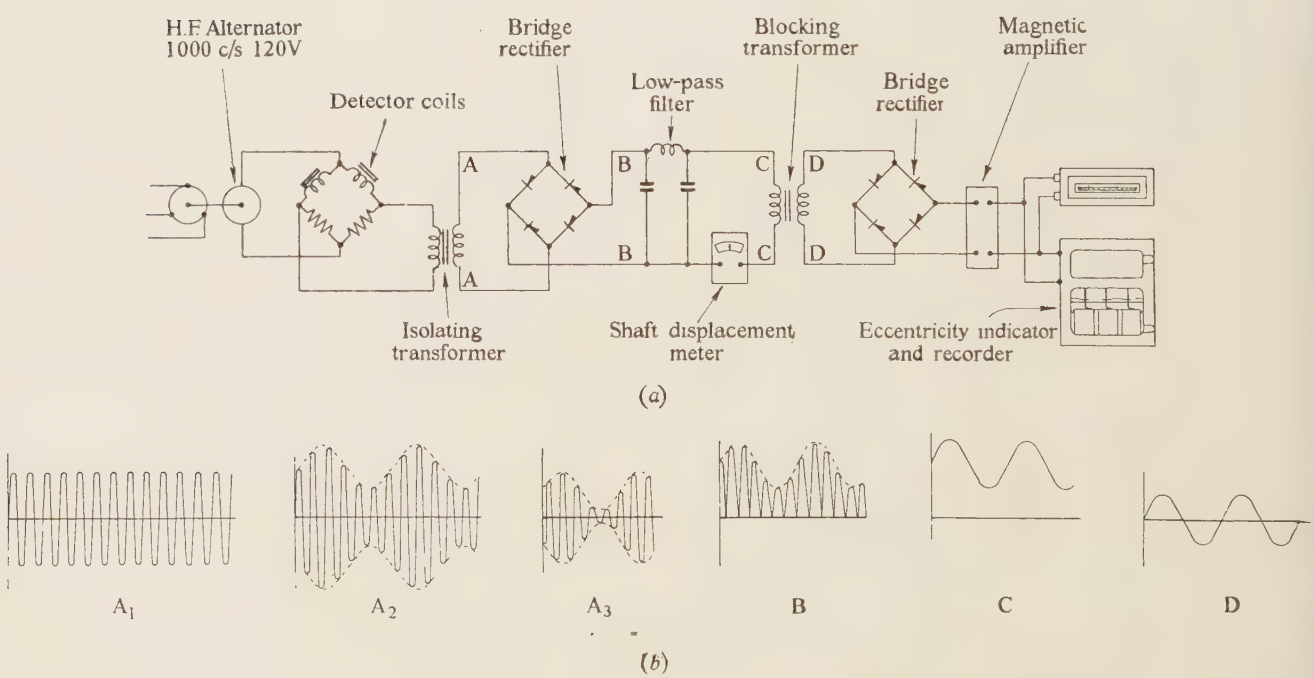


Fig. 2.—Circuit showing the basic principle of detection of eccentricity of the shaft.

(a) Simplified circuit diagram.
(b) Waveforms at various points.

of the null point. Thus when the turbine shaft is at rest the out-of-balance voltage at AA may be represented by the carrier wave shown at A_1 in Fig. 2(*b*). As the shaft turns, not only may its axis rotate eccentrically, but also its mean position may move relative to the coils. The first of these motions has the effect of varying cyclically the detector-coil impedance and hence the out-of-balance voltage, so that the carrier wave is modulated as at A_2 in Fig. 2(*b*), the depth of modulation being proportional to the shaft eccentricity. The second motion of the shaft, i.e. of its mean position relative to the two coils, also changes the air-gaps of the coils, provided that the movement is towards or away from them. However, since the motion in this case is not related to the shaft speed and is relatively slow, it alters the mean value of the carrier wave, and a modulated waveform similar to A_3 in Fig. 2(*b*) may result.

The shaft motion is now represented electrically at the output terminals of the bridge by a modulated carrier wave, and the function of the rest of the circuit is to translate this wave pattern into a form suitable for measurement by ratiometer instruments. The modulated carrier is first passed through an isolating transformer of suitable frequency response, which prevents interference between the modulation in the vertical and horizontal detection circuits. The modulated carrier, as represented by A_2 in Fig. 2(*b*), is then fed to a bridge rectifier circuit, whence it emerges as the waveform B. This signal is passed through a low-pass filter to remove the high-frequency components, leaving a low-frequency a.c. signal superimposed on a d.c. signal, the latter being proportional to the mean bridge out-of-balance, i.e. to the mean shaft displacement. The d.c. signal is measured at this point by a ratiometer ammeter calibrated from $-0{\cdot}02$ in to $+0{\cdot}02$ in with a centre zero. Zero adjustment is provided by a potentiometer incorporated in the bridge circuit.

Reverting to the eccentricity detection, the stage is reached at CC, in Fig. 2(*a*), where the mean shaft displacement has been indicated as a d.c. signal, leaving the low-frequency modulation indicative of the shaft eccentricity. The d.c. signal is blocked at this point by a transformer of approximately 1 : 1 ratio having a uniform frequency response over the range 1–50 c/s. The eccentricity signal, in the form indicated by D in Fig. 2(*b*), is fed to a further bridge rectifier circuit from which it emerges with a d.c. component. This d.c. signal is a function of the depth of modulation, and could be connected to an indicating instrument. It has insufficient power to work a recorder, however, and so a magnetic amplifier is inserted in the circuit. The eccentricity signal is thus amplified before being fed to a visual indicating instrument and a chart recorder, both of which are of the ratiometer type and are calibrated from 0 to $0{\cdot}015$ in. Suitable potentiometers are incorporated in each magnetic

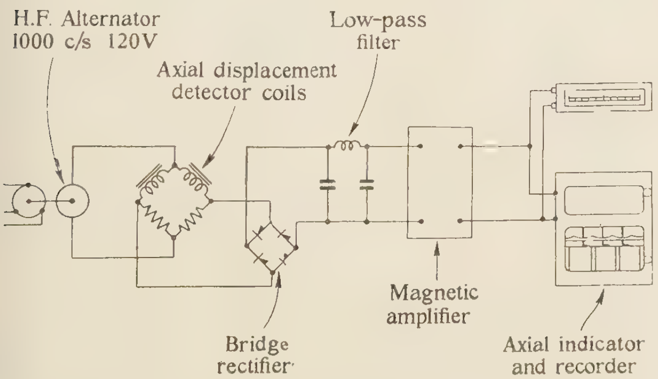


Fig. 3.—Circuit showing basic principle of detection of axial movement of the shaft.

amplifier so that the appropriate gain and zero setting may be obtained.

In addition to the two pairs of coils disposed around the disc on the turbine shaft, another pair is used on opposite faces of the disc to detect motion in an axial direction. As before, the change in the air-gaps between the coils and the disc, as the disc and shaft move axially, cause a change in the impedance of the coils. The circuit used for translating this into a current measurement is shown in Fig. 3, in a simplified form. The bridge is deliberately unbalanced. The high-frequency carrier is rectified and filtered to produce a d.c. signal which is amplified and fed to a visual indicator and chart recorder scaled from $-0{\cdot}250$ in to $+0{\cdot}250$ in. As with the instruments for indicating eccentricity, suitable potentiometers are incorporated in the magnetic amplifier to adjust the gain and zero settings.

(2.2) Motor-Generator Set

Any form of a.c. generator could be used to provide the supply at 120 volts and 1 000 c/s, the two obvious alternatives being a valve oscillator and a rotary machine. Since the equipment is required to operate in a power station, robustness is essential, and freedom from the need for maintenance is very desirable; therefore an inductor-type alternator was chosen.

The alternator, which is driven by a 3-phase induction motor rated at 1 h.p., has a rotating field system comprising two claw-type pole pieces, one on each side of an annular permanent magnet. Each pole piece has 21 projections, so that when assembled they interlink to form 42 poles of alternate polarity.

It was found desirable, in the assembly of the alternator, to machine the periphery of the rotor to ensure that it was concentric with its shaft bearings. This is important, because any eccentricity of the rotor with respect to the stator would induce a 50-c/s signal superimposed on the 1 000-c/s output, which in turn would interfere with the modulation produced by the eccentricity of the turbine shaft. A rigid coupling between the alternator and motor was also found necessary to ensure that torsional oscillations of low frequency are not set up in the coupled shafts. Such oscillations would produce frequency and amplitude modulation of the output which would disturb the signals of the eccentricity detector.

(2.3) Supply for Control Coils of Ratiometer Instruments

Mention has been made of the use of ratiometer instruments. This type of instrument was chosen to minimize errors caused by the fluctuation of the system frequency and voltage. The deflection current is compared with a reference current obtained direct from the 1 000-c/s alternator, through a suitable rectifier and filter network.

If the compensation is not perfect over the whole range for the combination of magnetic amplifiers and ratiometer instruments, the final correction may be given by a suitable inductance in the reference-current circuit.

A supply-system frequency variation from $47{\cdot}5$ to 51 c/s changes the h.f. alternator voltage by about 8%, but the readings obtained are not affected by more than 1%.

(2.4) Provision of Calibrating Signals

Incorporated in the equipment are means for producing calibration signals for all three circuits, so that it is possible to check at any time whether the sensitivity of these circuits is the same as at the time of initial calibration. The calibration signals for the horizontal and vertical eccentricity circuits are produced by a disc of known eccentricity fitted to the end of the 1 000-c/s alternator shaft. It rotates between two small detector coils

mounted diametrically opposite and around the periphery of the disc. These detectors are connected in bridge form and simulate the action of the main bridge circuits. They may be inserted in the circuit in place of the detector coils in the turbine casing. The calibration for the differential axial expansion is produced by a voltage tapped from the main 1 000-c/s supply. A rotary switch enables the calibration signals to be injected into the three circuits simultaneously.

(3) INDICATION OF SHAFT MOTION BY AN OSCILLOGRAPH

In addition to the visual-indicating and chart-recording instruments, provision is made for the study of the shaft eccentricity using a cathode-ray oscillograph. The eccentricity signals, at the point C in Fig. 2(*a*), from the vertical and horizontal detector circuits are respectively applied to the vertical and horizontal deflection plates of the oscillograph. The trace, accordingly, follows the eccentric motion of the end of the shaft.

(4) TEST RIG

Overall calibration of the supervisory equipment is carried out during manufacture, only a few check calibrations being then required when it is fitted to the machine. To simulate the motion of the turbine shaft a test rig was built, comprising a steel disc, the diameter of which is the same as the disc machined on the turbine shaft, rotated by a geared motor. The disc can run at speeds up to 3 400 r.p.m. The end of the spindle upon which the disc is clamped has an eccentric taper, and the disc has a hole of equal taper and eccentricity so that, by altering the angular clamping position of the disc, known radii of eccentricity in the range 0–0·015 in may be obtained. The bronze ring which carries the detector coils is fixed to a movable frame which is constrained to move horizontally and axially with respect to the disc, thus simulating horizontal displacement of the shaft and differential axial expansion. Movement of the frame, which slides on the bedplate of the rig, is measured by dial micrometers.

(5) THE SHAFT DISC AND ITS MAGNETIC PROPERTIES

The disc around which the detector coils are placed may be either integral with the shaft, or a separate disc attached to the shaft. The integral disc is to be preferred for its mechanical reliability, and the first installation made was of this form. It does, however, require the shaft forging to be of a material with suitable and uniform magnetic properties.

The use of a separate disc requires means of securing the disc firmly and accurately to the shaft, but has the advantages of allowing a free choice of disc material, and enabling the calibration of the equipment in the test rig during manufacture to be made with the actual disc.

Initial experiments on the measurement of eccentricity with the test rig and detector circuits showed the importance of making the disc of a material with uniform magnetic properties. For the first tests a steel disc of unknown composition was used, and it was found that the variation of permeability around its periphery produced spurious results. A disc cut from a rotor forging which had had the same heat treatment as a turbine shaft showed practically no departure from uniformity, and was used for calibrating the equipment.

Not all rotor forgings are magnetically suitable, and discs built up of laminations can be used to avoid the difficulty of finding material for separate discs having the desired magnetic uniformity.

The circuit for detecting axial displacement is, of course, unaffected by any non-uniform magnetic properties of the disc, since it operates according to the mean degree of unbalance of the bridge over the cycle of rotation.

(6) AIR-GAP SETTINGS OF THE DETECTOR COILS

In order that the response of the detector coils to shaft motion may be interpreted easily, it is necessary that the variation of bridge output with disc position should be linear over the maximum range of excursion. If the bridge circuit is symmetrical (i.e. if there is no initial unbalance) and if the air-gaps are equal when the disc is central, then the current/displacement curve is symmetrical, but not necessarily straight, as shown in Fig. 4(*a*).

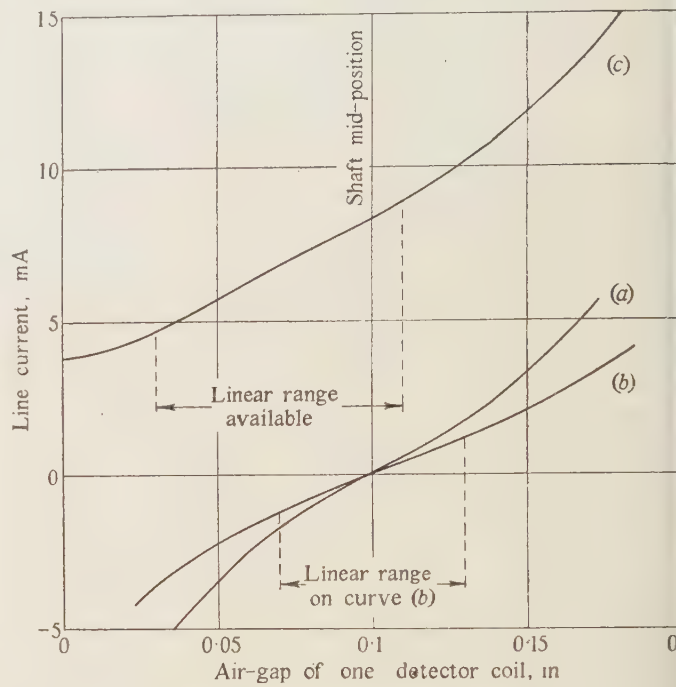


Fig. 4.—Shaft displacement curves.

The departure from rectilinearity is appreciable with small air-gaps. By widening the gaps a condition can be found for which the characteristic is substantially straight between the two extremes of possible travel of the disc centre, as shown in Fig. 4(*b*), but this causes a loss of sensitivity, which is, however, readily accommodated by the magnetic amplifier.

It has already been mentioned that the bridge is set up with an initial unbalance, by having unequal resistance arms, so that the resulting bridge current is never zero. This unbalance is reflected in the current displacement characteristic, which is asymmetrical about the shaft mid-position, as shown in Fig. 4(*c*). This asymmetry may be counteracted by setting up the air-gaps unequally. The arrangement provides an eccentricity measurement which is independent of mean shaft position within the range of possible travel.

A similar technique of using unequal air-gaps to achieve a symmetrical and substantially rectilinear response from the bridge was also used in the circuit for detecting axial displacement.

(7) PERFORMANCE OVER A RANGE OF SHAFT SPEED

The eccentricity signal takes the form of a modulated carrier wave, from which the carrier-frequency component is subsequently filtered after rectification. On starting from rest, therefore, the eccentricity instrument at first indicates an oscillating value corresponding to the changing peak value of the

carrier component. Owing, however, to the inertia of the instrument movement the amplitude of oscillation of the indication falls as the frequency increases until, at a speed of about 300 r.p.m., the needle is at rest at a position equivalent to the mean value of the carrier component. From this speed upwards to an overspeed value of about 3 400 r.p.m. the eccentricity value is indicated correctly, and independently of the speed of rotation.

Removal of the cyclic motion at low speeds is possible but would require some modification of the means of measurement over the range below 300 r.p.m. The indication provided as described above was considered adequate, however, since readings below 300 r.p.m. could, if required, be obtained directly by means of a dial gauge.

During the course of investigating the higher shaft-speed range over which the instruments would operate satisfactorily, difficulties were caused by vibration of the test-rig framework. When the steel disc was rotated eccentrically at speeds above 2 800 r.p.m. the out-of-balance force was sufficiently high to deflect elastically the pedestal on which the disc was mounted, thus disturbing the cyclic change in the air-gap, and hence the eccentricity reading. Consequently the framework was made considerably more rigid before reliable calibration measurements were made.

(8) CALIBRATION OF INSTRUMENTS

It has already been mentioned that the various instruments were calibrated on a test rig which simulated the expected shaft distortions.

Shaft-displacement tests were made on the rig by sliding the framework supporting the detector-coil ring in a horizontal direction transverse to the axis of the disc. A linear relationship was obtained between the direct current measured at CC in Fig. 2(*a*) and the disc displacement. Similar tests were then made on the disc machined on the turbine shaft, and an identical increment of reading was obtained for a given travel.

Tests were carried out with the disc rotating at various eccentricity settings, and the corresponding d.c. signal was measured at the output of the magnetic amplifier shown in Fig. 2(*a*). Each increase of eccentricity gave a corresponding proportionate increase in the depth of modulation of the carrier wave [A_2 in Fig. 2(*b*)] and hence in the resulting a.c. signal. For the purpose of recording the a.c. signal, however, it was necessary to rectify it, so giving an output corresponding to the non-linear rectifier characteristic, as in Fig. 5. It is impossible to work with signals sufficiently large to make the non-linearity negligible, because

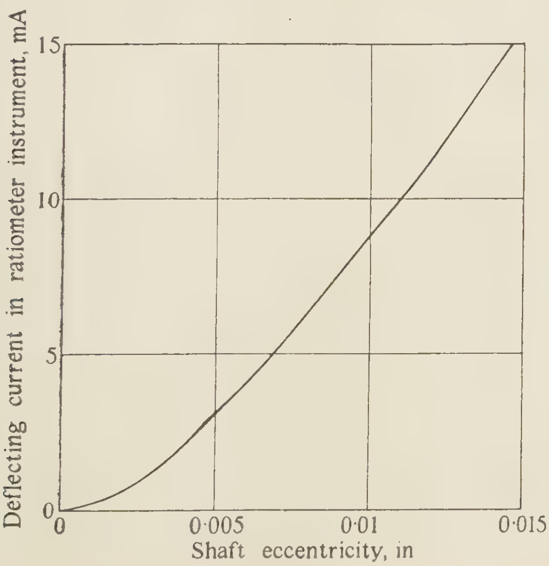


Fig. 5.—Calibration of horizontal- and vertical-eccentricity instruments.

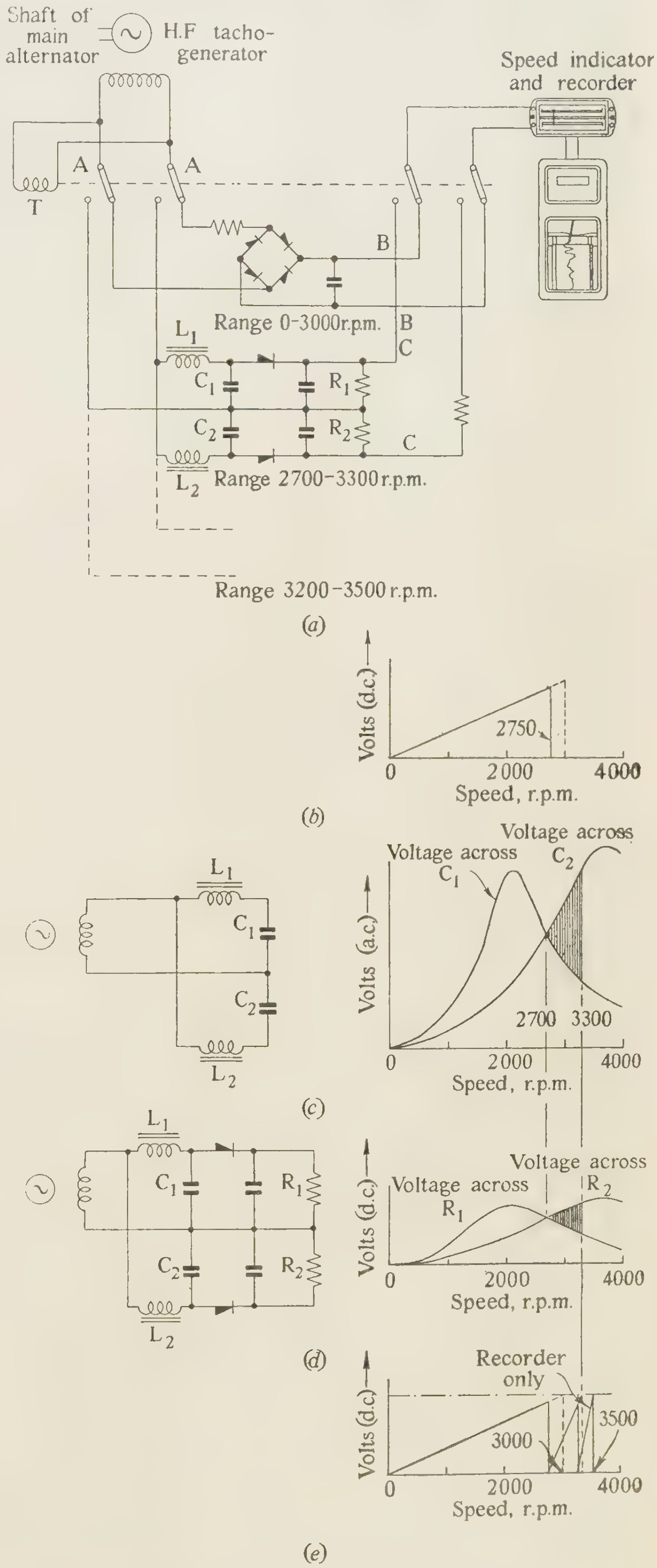
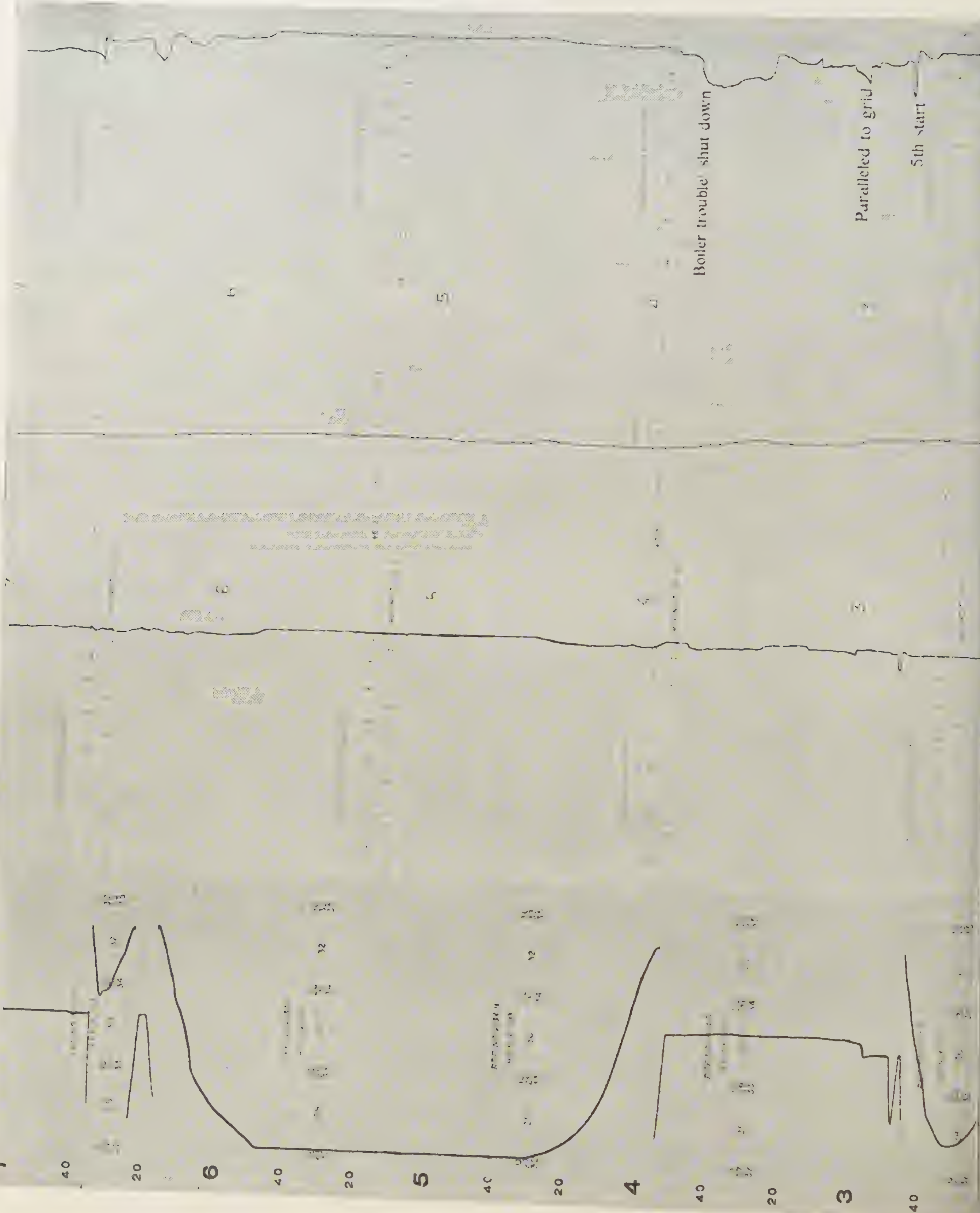


Fig. 6.—Simplified circuit diagram and output characteristics of speed-indication equipment.


Boiler trouble shut down
Paralleled to grid
5th start
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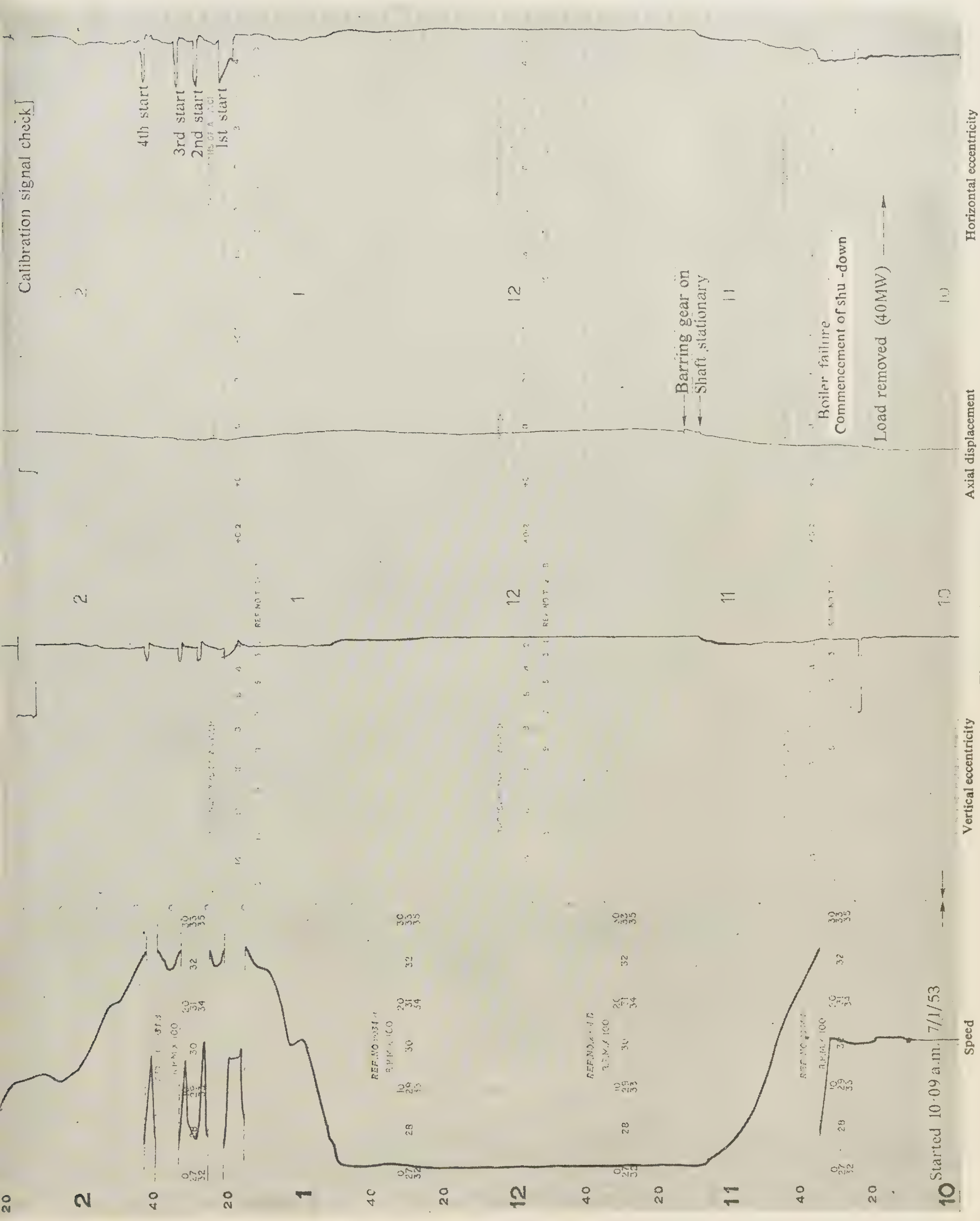

Fig. 7.—Chart record.

the principle of operation of the detector equipment demands that the rectifiers between the blocking transformer and the magnetic amplifier must accept near-zero signals. It is of interest to note at this stage that the rectifiers immediately following the isolating transformers are never required to rectify near-zero signals, so that their output characteristics are always virtually linear.

Calibration of the axial-displacement instrument was carried out in a similar manner.

(9) EFFECT OF VIBRATION OF THE DETECTOR-COIL RING

It is possible that the casing on which the detector-coil ring is mounted may vibrate. The vibrations will cause signals similar in character to and superimposed upon those caused by shaft eccentricity. The resultant complex signal cannot be resolved into the eccentricity and vibration components, since these may differ in frequency and phase relationship. Nevertheless, this complex signal does give the motion of the shaft with respect to the casing, which is the main purpose of the equipment.

(10) SHAFT SPEED

(10.1) Principles of Measurement

The voltage and frequency of the output of a permanent-magnet high-frequency alternator directly coupled to the turbo-generator shaft are directly proportional to the speed of the shaft. This property is used to indicate and record the speed of the turbine.

This small alternator is identical in construction with that used for the shaft-distortion circuits, except that it is flange-mounted and is driven by a quill shaft passing through the hollow mainshaft; the splined drive at the end of the quill shaft accommodates any radial or axial movement of the shaft of the main generator.

In Fig. 6(*a*), as the turbine speed increases from rest, the output of the h.f. alternator at AA increases proportionately. This output is rectified and the resulting d.c. signal at BB varies as shown in Fig. 6(*b*), and is fed to a visual indicating instrument and chart recorder. These are arranged to have linear scales from zero to full-scale deflection at 3 000 r.p.m. When a speed of 2 750 r.p.m. is reached the output of the alternator is automatically switched, by a relay T, to series resonant circuits, as shown in Fig. 6(*a*). The first circuit comprises an inductor L_1, of very low resistance, in series with a capacitor C_1, and is arranged to resonate at about 840 c/s (2 400 r.p.m.); the second circuit, L_2 and C_2 in series, resonates at about 1 260 c/s (3 600 r.p.m.).

The resonance curves for the tuned circuits are shown in Figs. 6(*c*) and 6(*d*) corresponding to the potential differences across C_1, C_2, R_1 and R_2. It will be noted that the curves intersect at a frequency corresponding to a speed of 2 700 r.p.m. The potential difference across CC is the difference between the potential differences across R_1 and R_2, i.e. it is represented by the ordinate, at any instant, between the two resonance curves. This output is fed directly to the indicating and recording instruments. The voltage which appears across CC is zero at 2 700 r.p.m. and has a value equal to full-scale deflection of the instruments at 3 300 r.p.m.

At 3 250 r.p.m. another relay is energized which transfers the output of the h.f. alternator to a network of tuned circuits similar to those used for the previous range. Thus the input to the recording instrument is zero at 3 200 r.p.m. and reaches a value which gives full-scale deflection at 3 500 r.p.m.

The change in input signal to the instruments over the complete frequency range from 200 to 3 500 r.p.m. is shown in Fig. 6(*e*).

(10.2) Calibration of Instruments

The sensitivity of the equipment was higher than that of available mechanical tachometers and stroboscopes, so these instruments could not be used for the speed calibration.

A method of calibration has been adopted involving the use of a cathode-ray oscillograph in conjunction with an electrical test rig. This rig consists of a variable-speed drive representing the turbo-alternator shaft, coupled to the h.f. alternator. A signal from the h.f. alternator is compared with a 1 000-c/s reference signal from a quartz-crystal oscillator. These signals are fed to the plates of the cathode-ray oscillograph, and produce a series of patterns on the screen in the form of Lissajous figures. Each stationary pattern represents a precise speed of the h.f. alternator; thus a large number of accurate check-points are obtained throughout the speed ranges.

It will be appreciated that full advantage of the sensitivity of this equipment has not been taken. With the equipment in its present form changes of speed as low as 1 r.p.m. (1/60 c/s or $0{\cdot}033\%$ of mains frequency) can be detected. Arrangements could easily be made to detect smaller speed changes of the order of 0·2 r.p.m. with the equipment described.

(11) OPERATING EXPERIENCE

The supervisory equipment has been used on a number of steam trials of turbines at the factory, when both normal and abnormal conditions of balance, starting sequence, foundation arrangement, etc., could be applied. Much valuable experience was gained during these tests. The equipment has also been fitted to the 60-MW two-casing turbo-alternator sets at the British Electricity Authority's power station at Uskmouth, and has been in commission since December, 1952.

When the set is running normally on steady load the vertical and horizontal eccentricity measurements are in fair agreement, and do not exceed about 0·003 in. If the machine is brought up to speed and loaded too quickly, before the temperatures of rotor, casing, lubricating oil, etc., have become sufficiently stable, the eccentricity may rise and so give warning of impending danger. If the starting schedule is not properly followed, e.g. if the barring gear is stopped, or not run for a sufficient time, then the result is evident in the increased eccentricity.

As supervisory instruments of this type are a relatively recent innovation, there is not yet sufficient experience on a wide range of machines to give guidance in the interpretation of the records. Information is being gained each day, and as this accumulates it will form a background against which future records can be viewed more critically. Despite the limited experience, much interesting information may be deduced from the records, as can be seen from the following examples.

Fig. 7 presents the record of the following sequence of events. The alternator set was running normally at 3 000 r.p.m. and 40-MW load. The vertical eccentricity was less than 0·001 in; the horizontal eccentricity was approximately 0·003 in; and the differential axial expansion was +0·045 in. At approximately 10.18 a.m. difficulties were experienced with some of the ancillary boiler equipment, so much so that the load of 40 MW was taken off the set in the course of a few minutes. It will be seen that no change in the eccentricities occurred, but the differential axial movement proceeded immediately in a negative direction, i.e. the shaft shrank relative to the casing. At 10.32 a.m. it was decided to shut the set down until the boiler ancillaries had been satisfactorily adjusted, and it is seen from the speed chart that the run-down was uniform, occupying the next 35 minutes. During this time the vertical eccentricity increased first to 0·0015 in and later to nearly 0·002 in, while the horizontal eccentricity decreased immediately to 0·0025 in, and thence

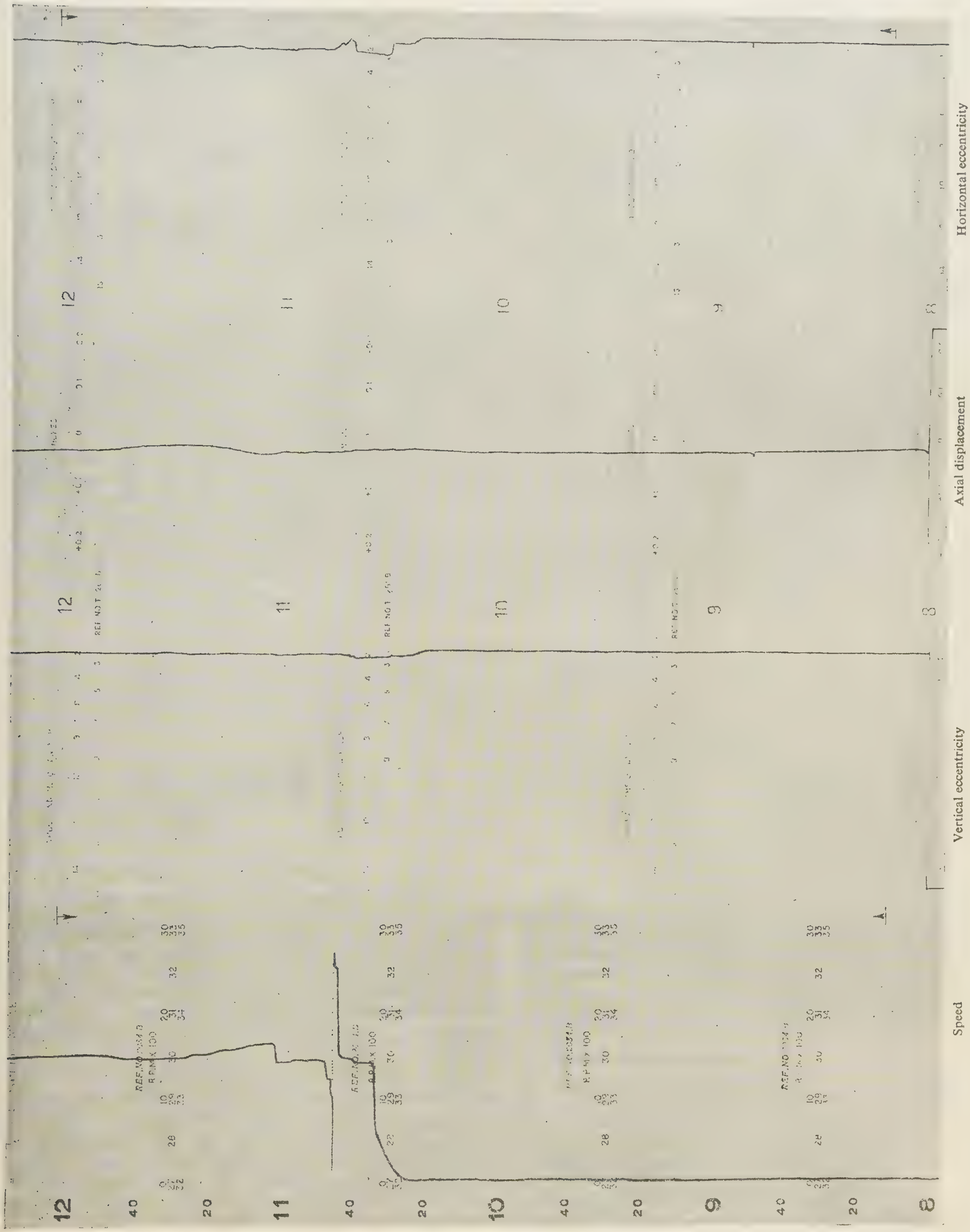

Fig. 8.—Chart record.

more or less uniformly to 0·002 in. One significant point is that over the rundown range of 1 250 r.p.m. to zero the eccentricity recordings were identical, whereas at speeds above this range the horizontal eccentricity increased while the vertical eccentricity decreased. Insufficient evidence exists at this stage to indicate a reason for this phenomenon, but it is hoped that further information will become available as the remaining five turbo-alternator sets are commissioned.

At 11.07 a.m. the turbine shaft came to rest, but owing to an oversight the barring gear was not engaged until 11.12 a.m. At 12.45 p.m. the boiler adjustments were completed and an attempt was made to restart. As the speed increased to 1 800 r.p.m. the horizontal and vertical eccentricity readings increased to approximately 0·002 in. Further increases in speed up to 3 000 r.p.m. led to a large increase in the horizontal, and to a lesser extent in the vertical eccentricity and it was thought that the five-minute period during which the shaft was stationary might have caused the shaft to bend as a result of uneven cooling. These eccentricities were considered too great to be allowed to continue, and the speed was reduced to 2 500 r.p.m. Three more attempts were made to get the set up to full speed, but eccentricities of 0·0055 in were recorded. It was then decided to reduce speed for about half an hour to see whether the shaft would straighten itself under the action of the steam. During this time an opportunity was taken at 2.13 p.m. to check the accuracy of the detection circuit with the calibration signals. These were observed to be as originally set. At 2.35 p.m. a fifth attempt was made to bring the set up to speed and eventually at 3.02 p.m. the set was paralleled to the Grid, the shaft eccentricities being 0·003 in horizontally and 0·001 in vertically. From then until 3.50 p.m. further boiler trouble was experienced, so much so that the alternator load was varying between 5 MW and 50 MW continuously, the effect of which may be seen on the erratic trace of the horizontal eccentricity. Eventually, at 3.52 p.m., a further shut-down was deemed necessary. A restart was made at 5.45 p.m. and it can be seen that the eccentricities were not as great as before, the maximum being 0·004 in. The set returned to full load at 7.15 p.m.

Fig. 8 shows the distortions which occur during normal starting conditions, and includes several interesting eccentricity changes. Owing to slight misalignment of the pens and errors in time setting of the chart, the speed chart is four minutes in advance of the shaft-distortion chart. Both the vertical and horizontal eccentricities were of the order of 0·001–0·0015 in from 300 to 600 r.p.m. When the speed was suddenly increased to about 1 500 r.p.m. the vertical eccentricity remained substantially constant while the horizontal eccentricity increased from 0·001 in to 0·0025 in. After ten minutes at these conditions the speed was increased to 3 000 r.p.m., and it can be seen that the vertical eccentricity began to fall slightly while the horizontal eccentricity fell rapidly to zero. During the next few minutes at 3 000 r.p.m. the horizontal eccentricity rose to 0·002 in, the vertical eccentricity remaining practically constant. The abrupt changes in the values of horizontal eccentricity may be attributed to the reasons already advanced in Section 9; that is to say, the presence of other disturbing effects which cause unbalance. As the supervisory gear measures the relative motion of the disc in the bearing housing or casing, the reading is then not merely of eccentricity, but represents a combination of the effects of bending of the shaft (eccentricity of disc), movement of the shaft axis in space, and movement of the bearing housing in space. The relative motions may be influenced also by the clearance between journal and bearing, by the viscosity of the oil, by gravitational forces and by unequal or non-linear stiffness of the bearing housing and foundation in vertical and horizontal directions. In such cases the motions, though small, may be very complex, and the horizontal indications are generally appreciably greater than the vertical, as will be seen in Fig. 8.

(12) CONCLUDING REMARKS

The continuous indication of the state of running of the turbo-alternators at Uskmouth has been a valuable guide to the drivers during both starting and running, and the charts of the various measurements have been a useful record to enable the station staff and manufacturers to analyse the performance of the sets.

The limited experience gained has already served to indicate where improvements can be introduced to make the equipment and its records more effective. Any shaft distortions which take place are found to be so closely associated with the speed and load of the set, at any particular moment, that it is of great value when interpreting the records to have these quantities recorded on the same chart as that showing the shaft distortions. This recording arrangement is incorporated in equipment now being installed elsewhere.

Up to the present, after many months of continuous operation of the equipment on the sets at Uskmouth, no maintenance has been necessary, thus fulfilling the reliability requirements.

(13) ACKNOWLEDGMENTS

The authors wish to thank the Director of the Research Laboratories, The General Electric Company, Limited, for permission to publish the paper. They are indebted to their former colleague Mr. J. K. Barugh for his valuable assistance in the initial stages of the work.

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[The discussion on the above paper will be found on page 147.]

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Paper No. 1680 S
Sept. 1954

THE ELECTRICAL MEASUREMENT OF STEAM-TURBINE ROTOR MOVEMENTS, WITH SPECIAL REFERENCE TO THE OPERATION AND DESIGN OF MODERN POWER PLANT

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(*The paper was first received* 23rd *October*, 1953, *and in revised form* 29th *March*, 1954. *It was published in September*, 1954, *and was read before the* NORTH STAFFORDSHIRE SUB-CENTRE 22*nd November*, *a Joint Meeting of the* SUPPLY SECTION *and the* STEAM GROUP *of* THE INSTITUTION OF MECHANICAL ENGINEERS 24*th November*, *and the* NORTH-WESTERN SUPPLY GROUP 30*th November*, 1954.)

SUMMARY

The paper shows how the increased size and higher operating steam temperatures and pressures have led to the introduction of electrical turbovisory equipment. It describes how the gear presents to the turbine operator a continuous record of the behaviour of the rotor during the whole period of starting and running on load. Experience gained with some 60 sets of equipment now in use, some of which have been in service for the past nine years, is considered in some detail.

Examples are given of eccentricity and differential-expansion charts recorded in service. These relate to occasions when the turbovisory equipment indicated abnormal conditions and enabled corrective action to be taken before damage occurred. These examples are discussed in detail, and explanations of the causes of the abnormalities are suggested. The interpretation of eccentricity records is discussed, particularly with reference to the problems encountered in starting turbines.

A further Section indicates how these measurements have led to a better understanding of these problems, leading in some cases to improvements in turbine design. Finally, the future trend of turbovisory equipment is considered.

(1) INTRODUCTION

The steam turbine holds an important place in modern life and much depends on its reliability. It has been developed, largely on the basis of accumulated experience, from small ratings operating with low steam conditions to the modern large power-station machines of 100 MW or more, using steam at high pressure and temperature.

It is also mainly on the basis of accumulated experience that turbines have been operated, and a tradition of high competence has been established amongst turbine drivers. However, the employment of progressively higher steam conditions has increased the significance of those problems of operating technique associated with mass and temperature, and as long ago as 1943 it became apparent that there was a need for instruments to augment the driver's skill.

In forming an opinion of the type of problem involved it will be understood that in large modern turbines rotors weighing several tons are running at speeds up to 3 000 r.p.m. where the inlet temperature, at least, may be in the region of 1 000°F. These rotors must remain geometrically true and accurately balanced. For instance, a distortion which caused the centre of mass to be displaced only 0·004 in from the axis of rotation would produce at 3 000 r.p.m. a centrifugal force equal to the weight of the rotor. A number of causes such as uneven heating or temporary malalignment may result in displacement. The outward sign is vibration; and sensitivity to vibration, combined with an insight into its cause and cure, has long been a mark of the competent turbine driver.

Increase in size and operating temperature has been rapid in the last few decades. The turbine itself now requires a greater capital outlay, and, equally important, the value of high availability has been correspondingly increased. With higher temperatures the possibility of significant temperature gradients due to uneven heating becomes greater. With larger sizes, the tolerable rotor distortions, which are independent of size, become relatively smaller—all of which are reasons for looking to scientific instrumentation to guide the operation of the larger machines.

The value of instrumentation is most apparent during starting, and it is a feature of present trends that machines are subject to more frequent starting and stopping. In this country the load curve of the public supply system requires a large number of machines to be run on an intermittent basis. Whilst at the present time the machines concerned are generally of the older lower-pressure type, it is expected that with the advent of the 275-kV transmission network, the number of machines liable to two-shift operation will greatly increase and will include comparatively large machines operating at high steam pressures and temperatures. To secure economy under these circumstances it is essential that these machines should be shut down and subsequently restarted as rapidly as continued reliability and safety will permit. One of the main uses of turbovisory equipment is to aid in the development of quick-starting techniques and to provide a guide to control when the technique has been established.

The control of transverse rotor deflection is, perhaps, the most important problem during rapid starting; a prime function of turbovisory equipment is therefore to give the driver warning of deflection in advance of the onset of noticeable vibration, particularly at low speeds in the course of running up, when continued increase in speed might produce conditions which would be out of control by the time the senses became aware of vibration. The eccentricity indicator fulfils this need, and is perhaps the most important item of the equipment. Transverse deflection must be controlled within narrow limits, and consequently the eccentricity indicator must have a correspondingly high degree of sensitivity.

It is also a valuable aid to operation to have an indication of the axial clearances between moving and fixed parts inside a turbine, although a much coarser degree of control is quite satisfactory in this respect. Turbine rotors are located axially in the casing by means of a thrust collar usually placed at one end, outside the bearing at that end. When temperature changes occur, the rate of heating of the rotor is rarely the same as that of the casing, and consequently the two parts experience a differential axial expansion which is greatest at the end remote from the thrust collar. Under some conditions this differential

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expansion may be considerable and become dangerous. There are, of course, many places where the axial clearances between rotor and casing are of the order of $\frac{1}{16}$in to $\frac{1}{4}$in. Although attention to design minimizes the danger from differential expansion, it is a comparatively simple matter to fit an indicator. Many turbovisory equipments at present in use comprise eccentricity and differential expansion indicators. Fig. 1 shows

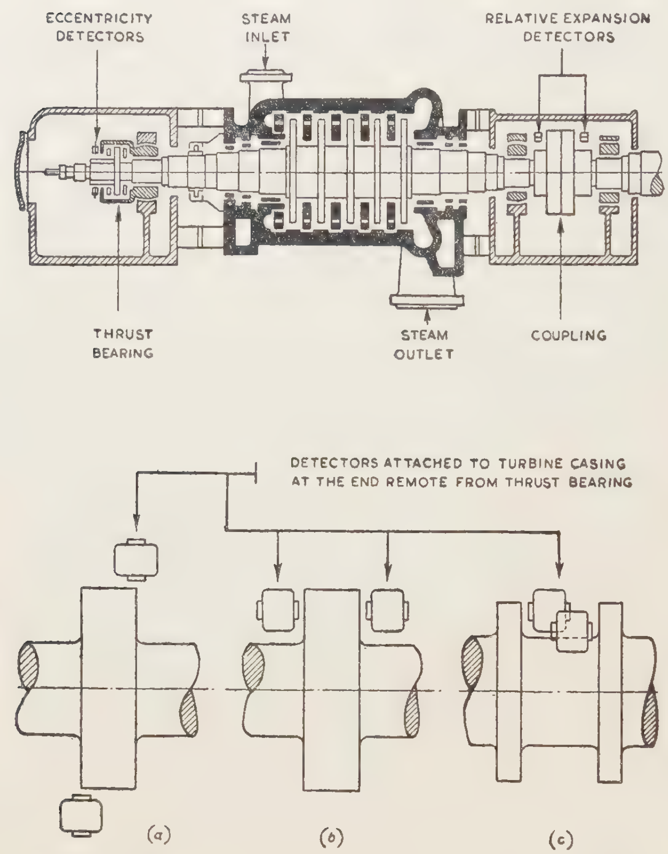

Fig. 1.—Location of detector magnets.

diagrammatically a turbine casing and rotor, and the location of the eccentricity and differential expansion detector magnets. In a two-cylinder condensing turbine, the equipment is usually fitted to the h.p. cylinder only. In a three-cylinder turbine it may be fitted to the i.p. cylinder in addition. So far it has not appeared necessary to fit it to l.p. cylinders.

Turbovisory equipment functions primarily as a concurrent aid to operation, but its value is greatly enhanced if it provides a record contributing to the operational history of the machine. For this reason the indicators are supplemented by recorders whose charts are thus available for reference. The scope of the equipment may be widened to cover additional information. The state of expansion of the turbine relative to the bed-plate has been found to be a valuable guide to operation in some instances, and certain steam and metal temperatures may have special significance. In examining records it is often important to know the speed of rotation, and a record covering the full range from zero to overspeed may be included.

The records obtained have also stimulated thought on why shafts deflect, on the limits of deflection which can be tolerated or on the steps which can be taken in design and operation to prevent deflection—this refers, of course, only to the type of transient deflection which can be corrected while the machine is still running.

(2) DESCRIPTION OF EQUIPMENT

(2.1) Differential Axial Expansion

As mentioned previously, differential axial expansion is the simpler of the two measurements used for keeping the behaviour of the rotor under observation. The early instruments were based on mechanical and optical principles. These were very useful but they suffered from mechanical wear, dirty lenses, etc., and it was clear that electrical instruments would be more permanent and could be arranged to provide a record more readily.

Two methods were examined, one employing a variable-capacitance network and the other a variable-inductance bridge. However, since the distances to be measured are large, i.e. up to 0·2in, a capacitance arrangement requires the complication of a "follow-up" device. Therefore the variable-inductance method is preferable.

In the variable-inductance method two basic positions of the detector magnets with respect to the moving part are possible. These are shown in Figs. 1(*a*) and 1(*b*). Position (*b*) was adopted, the coupling at the end of the rotor usually providing the required end faces on the moving part. This arrangement avoids any calibration difficulties associated with "end" effects which are present if position (*a*) is used, and furthermore it avoids any errors due to eccentricity of the shaft. An alternative method of mounting the magnet when the coupling cannot be used is shown in (*c*). The circuit is shown in Fig. 2.

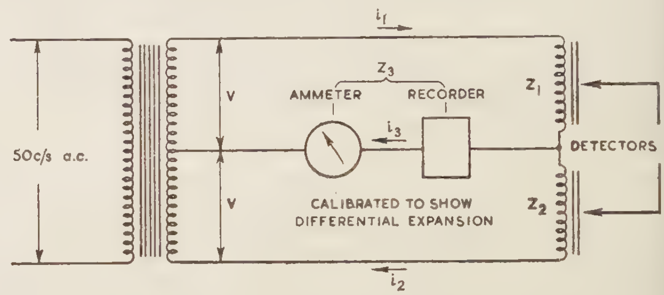

Fig. 2.—Basic circuit of differential-expansion equipment.

$$i_3 = \frac{V(Z_2 - Z_1)}{Z_1Z_2 + Z_3(Z_1 + Z_2)}$$

(2.2) Shaft Deflection

With shaft deflection, early improvisation with mechanical devices fulfilled the need to some extent while electrical methods were being developed. When electrical methods were studied, the relative merits of variable-capacitance and variable-inductance networks were again considered, and although the movements in this case are quite suitable for capacitance measurement, the possibility of variation in the permittivity of the atmosphere surrounding the probe determined the adoption of the variable-inductance network.

Initially it was thought that possible variation in the permeability of the turbine shaft might introduce serious errors, and to avoid these, early equipments had laminated rings shrunk on to the shaft underneath the detector magnets. Experience has shown this to be unnecessary, and later models make use of the shaft itself.

It is important to know the condition of the shaft at low speed, as well as at higher speed. The electrical problem posed thereby has been solved by switching in additional components when the turbine changes over from slow running to operation under steam.

(2.2.1) **Low-Speed Operation.**

The detector magnets are connected to a source of alternating voltage at a frequency of 500 c/s, and each forms a reactance in which the magnetic path is created by the detector core, the turbine shaft and two air-gaps, in series. As the shaft rotates, the length of each air-gap varies in amplitude according to the eccentricity of the shaft, and in periodicity according to the speed of rotation of the shaft. The basic circuit is shown in Fig. 3.

pass filter (L, C_1, R_2 and R_3), which eliminates the high-frequency components at the point B of the circuit but leaves the low-frequency modulation due to eccentricity unaffected. The waveform of the voltage existing at B is therefore as indicated in Fig. 3(*c*).

The filter is followed by a cathode-follower in which the output appears across the cathode load R_4; the waveshape at this point is the same as that at the input to the valve, except that

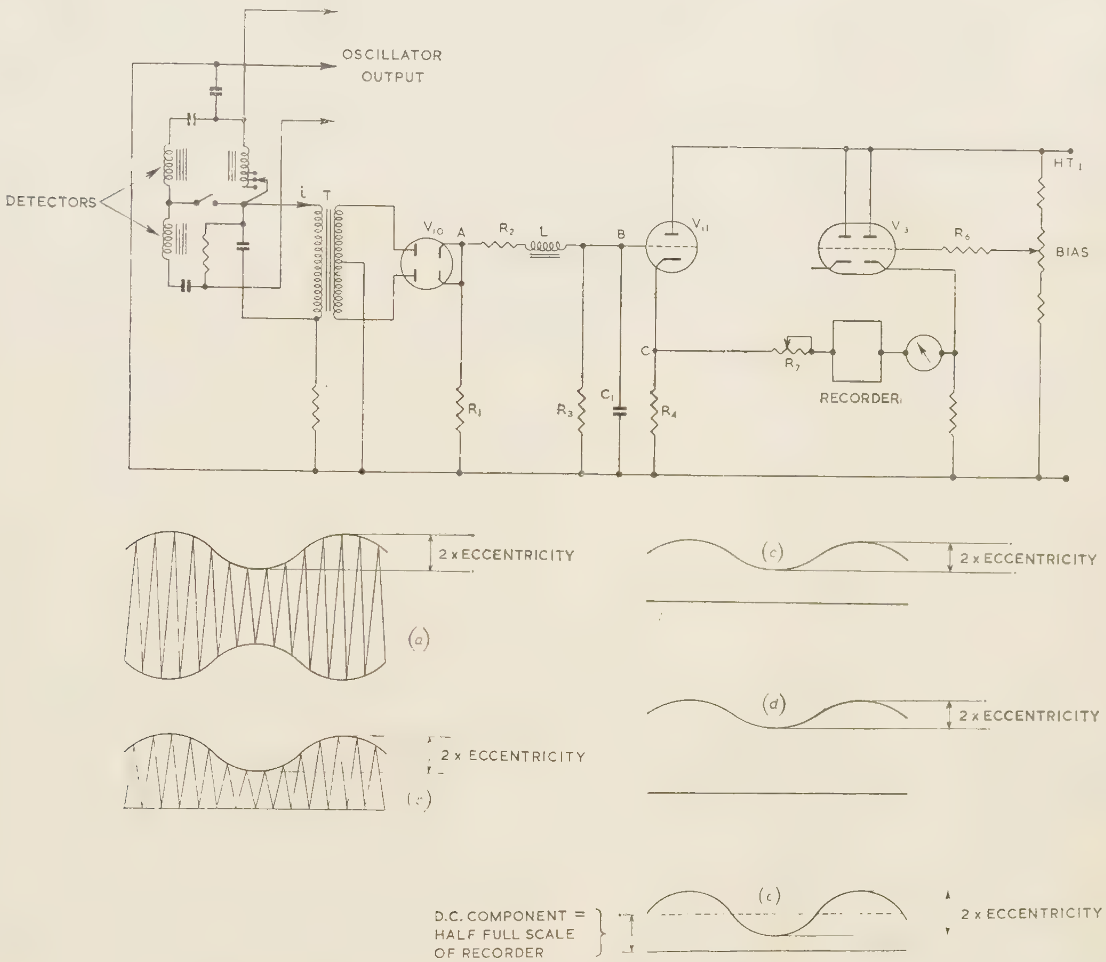

Fig. 3.—Basic circuit of eccentricity equipment; slow-running condition.

(*a*) Detector coil current.
(*b*) Rectified voltage at A.
(*c*) Voltage at B.
(*d*) Voltage at C.
(*e*) Recorder current *I*.

. modulated detector current, having a waveshape as shown in ig. 3(*a*), passes through the step-up transformer T, the secondary inding of which is connected to the resistor R_1 through a full-ave rectifying double-diode valve. The load thus introduced n the primary side of the transformer is resistive, but the esistance introduced into the detector unit is low and has no ppreciable effect upon the operation of the detector circuit. he transformer T may therefore be considered as a current ansformer, although the voltage across the resistor R_1 is of the rder of 50 to 100 volts. The waveform of this voltage Fig. 3(*b*)] is a fully-rectified version of the modulated coil ırrent.

The resistor R_1 is followed by a relatively high-impedance low-

the d.c. component is increased owing to the standing current through the valve, as shown in Fig. 3(*d*).

The amplitude of the low-frequency voltage across the cathode load R_4 is still a measure of the shaft eccentricity, and the recording instrument is operated directly from this voltage. Rheostats R_6 and R_7 provide a convenient method of varying the component of direct current through the recorder, and thus provide an adjustment of the sensitivity and electrical zero of the instrument [Fig. 3(*c*)].

Under conditions of low-speed rotation (say 2–5 r.p.m.), the pen of the recording instrument swings as though from the centre line of the shaft, and the total swing of the pen therefore records twice the eccentricity of the shaft.

(2.2.2) **Normal-Speed Operation.**

When running under steam the pen cannot follow the current modulations as at low speed, and a further translation becomes necessary in order to convert the depth of modulation into a steady direct current. A switch is operated, and the basic circuit now becomes as shown in Fig. 4. Up to the cathode

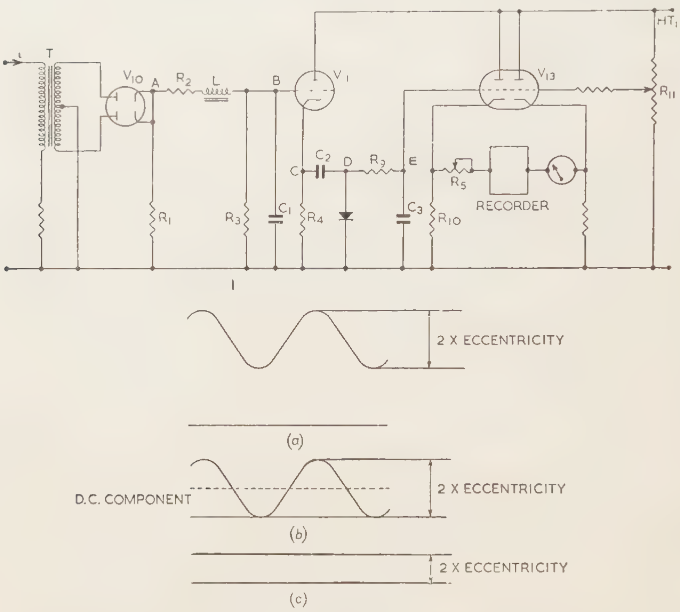

Fig. 4.—Basic circuit of eccentricity equipment; normal running condition.

(*a*) Voltage at C.
(*b*) Voltage at D.
(*c*) Voltage at E.

resistor R_4 the circuit remains as before, and thus the waveform of the voltage at C is as shown in Fig. 4(*a*). This voltage is applied through a condenser C_2 to a germanium crystal rectifier. Across the rectifier at the point D of the circuit there appears a voltage of the waveform shown in Fig. 4(*b*). The alternating component due to eccentricity is exactly the same as that across the resistor R_4, but in addition the direct component of voltage is half the total amplitude of the alternating voltage. This voltage is now applied to a low-pass filter R_9C_3 in which the alternating component of voltage due to eccentricity is removed, leaving at the point E across C_3, a direct voltage proportional to the eccentricity. This voltage is now converted into a power output across the cathode load resistor R_{10} by means of a second cathode-follower, the other half of this valve being used to balance out slight changes due to mains-voltage fluctuations.

The direct voltage across R_{10} is applied to the recording instrument through the rheostat R_5, which is included to give an adjustment to sensitivity. The adjustable biasing potentiometer R_{11}, fed from a stabilized h.t. d.c. supply, provides compensation for the direct voltage across R_{10} due to the standing current in V_{13}.

(2.3) Arrangement of Equipment

The equipment is arranged in sections comprising

(*a*) Detector magnets, junction boxes, for mounting on the turbine itself.
(*b*) Cubicle containing the power pack and oscillator, each cubicle providing sufficient power to feed four equipments.
(*c*) Cubicle containing eccentricity amplifier and axial expansion network.
(*d*) The two indicating instruments and duplex recorder.

The indicating and recording instruments are usually mounte on the turbine gauge board, and the two cubicles may then b mounted at some convenient place. The circuit, either norma speed or low-speed, is selected by a single switch, enabling on instrument to record either condition.

(3) RELIABILITY AND ACCURACY OF TURBOVISORY EQUIPMENT

Some 60 equipments now in operation have been in service fo periods up to nine years. Troubles have been few and hav usually fallen into one of the four following groups:

(*a*) *System Disturbance.*—Isolated erratic readings hav occurred from time to time with some equipments. These hav been traced to serious voltage disturbances on the auxiliar supply feeding the apparatus, mainly due to direct starting o large motors. Careful selection of the supply line and a improved form of stabilizer have completely eradicated thi trouble.

(*b*) *Detector Magnets.*—During routine examination it wa discovered that there were instances of the rubber covering o the magnets showing signs of deterioration owing to penetratio of oil through the protective vulcanized-rubber binding. Possi bility of trouble from this cause has been eliminated by the us of a moulded cover instead of rubber binding.

(*c*) *Leakage.*—On occasions the presence of steam round som equipments has introduced errors due to electrical leakage. I consequence the high-impedance circuits have been redesigned t reduce sensitivity to moisture.

(*d*) *Valve Life.*—When turbovisory gear was first introduced i was considered desirable to replace all valves at three-monthl intervals. The object was to relieve station staffs of responsi bility for valve maintenance. Subsequent experience has show that periodic replacement is unnecessary, and a simple mainten ance drill has been evolved whereby complete inspection of al equipment is achieved by means of integral test instruments This examines each part of the circuit and detects incipient fault including failing valves. At the same time it enables calibratio to be checked.

(*e*) *Accuracy.*—The eccentricity indicator is a sensitive instru ment capable of measuring to less than 0·001 in. It is not however, practicable to check the calibration of an instrumen under site conditions with the machine running, because n equally sensitive means of measuring the eccentricity is available Nevertheless, owing to the method of setting up, and using suc means of comparison as are available, it is probable that th absolute accuracy of measurement is within 0·001 in at lov eccentricities. In practice, this is found to be entirely satis factory.

(4) EXAMPLES AND DISCUSSION OF A SELECTION OF RECORDS FROM TURBOVISORY EQUIPMENT IN USE

It is now proposed to show a number of examples taken fro turbovisory records obtained during the past nine years.

(4.1) Two-Cylinder 60-MW Turbine

The first records to be shown refer to the routine operatio of one of the first machines to be fitted with turbovisory equip ment. It is a 60-MW two-cylinder machine running a 1 500 r.p.m. and taking steam at 600 lb/in^2 and 850°F from tw 400 000 lb/h pulverized-fuel-fired boilers, operating with th turbine as a unit.

When starting up, one boiler is brought up to the require pressure by "flashing" before steam is admitted to the turbine and pressure is maintained throughout the run-up by "flashing" as required; hence the initial steam temperature may be variabl and is considerably lower than when the set is on load.

A large machine of this type has a heavy cylinder which cools slowly during the shut-down period. The temperature of the steam during starting is often lower than that of the cylinder, particularly after a short shut-down, and the admission of this steam inevitably accelerates the contraction rate of the cylinder. Such a condition has been found from experience to lead to vibration if an attempt is made to run up to speed. It appears necessary to establish conditions of expansion to ensure a smooth run-up.

Contracting conditions were present when the chart shown in Fig. 5 was recorded. It refers to a start made after a 36-hour shut-down and shows the development and straightening of a severe transient bend. Eccentricity of the h.p. rotor began to increase when the speed was about 1 160 r.p.m. No improvement resulted when the speed was reduced a little, and steam was therefore shut off. Despite this, the eccentricity continued to increase, and before the machine came to rest, it had reached the limit of the recorder's travel (about 0·030 in). The barring record follows this incident and shows that the rotor returned to a straight condition after an hour of slow running. This record may hold the clue as to why the shaft experienced the temporary bend. It has been noted that the turbine structure as a whole was contracting. It can also be seen that the rotor was moving rapidly from a relatively contracting to a relatively expanding condition; it was being heated rapidly; the flexible coupling between the h.p. and l.p. rotors was sliding, either freely or a little sluggishly, in which case the thrust collar was being relieved of load, or may have crossed to the surge face.

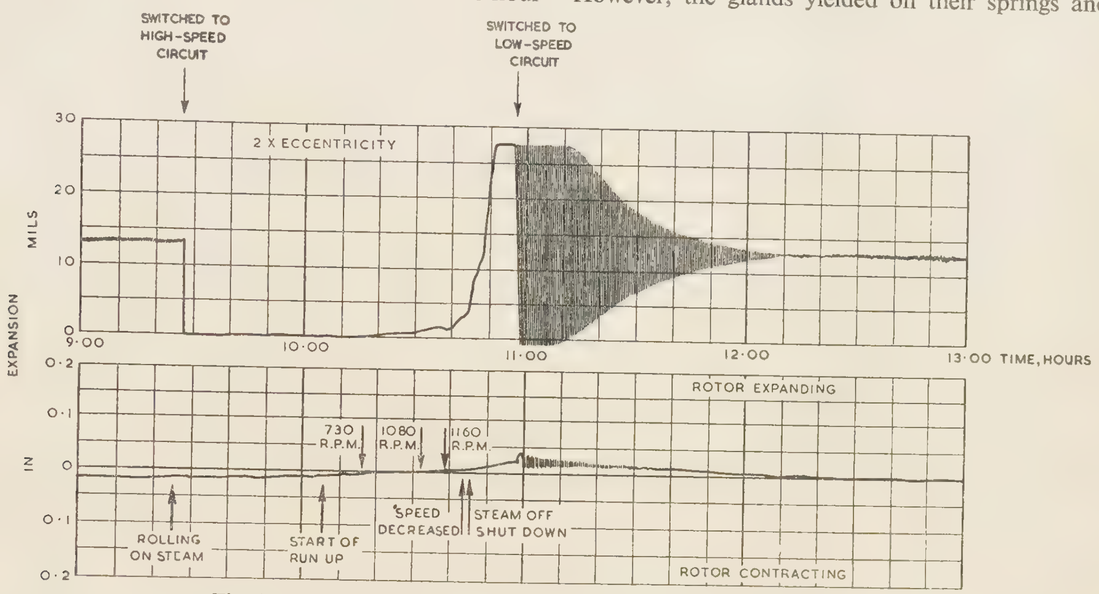

Fig. 5.—Record of start of 60-MW turbine after 36-hour shut-down.

Any mechanism whereby a contracting turbine can cause a rotor to bend, excluding the possibility of a touch, remains obscure. It is also difficult to conceive how any action connected with the sliding of the coupling can produce a bend, and we are left therefore to consider the rapid heating of the rotor. If heat flow into the rotor were uneven, a bend would be sure to ensue. Without discussing why the heat flow into the rotor was uneven, it does appear that, despite the fact that the turbine was contracting, the steam temperature was rising rapidly and the rotor was the first to feel the effect. The bend which still existed at the beginning of barring must have been thermal or it would not have been removed by the barring. It could have been caused by the heat effect of a rub consequent on the vibration caused by some sort of mechanical transient bend, but if so, more serious permanent trouble would have been experienced, because the rub would have increased the bend. Inspection of the machine showed some rubbing of the diaphragm seals, but no repairs were necessary, and the machine returned to service the next day.

Whatever the cause of the bend, the record is a striking testimony to the robustness of the modern impulse turbine. The large eccentricity must mean that the 10 ton rotor experienced a bend which produced centrifugal forces sufficient to whirl it round in the bearings almost to the limit of the clearance. However, the glands yielded on their springs and returned to normal afterwards, and there was no damage to blading or other components. The rotor straightened itself when the bending influence was removed. There is little doubt, nevertheless, that had the rotor been allowed to run with the transient bend, a severe rub would have occurred, resulting in a permanent bend.

The record of the run-up given in Fig. 6 again shows the

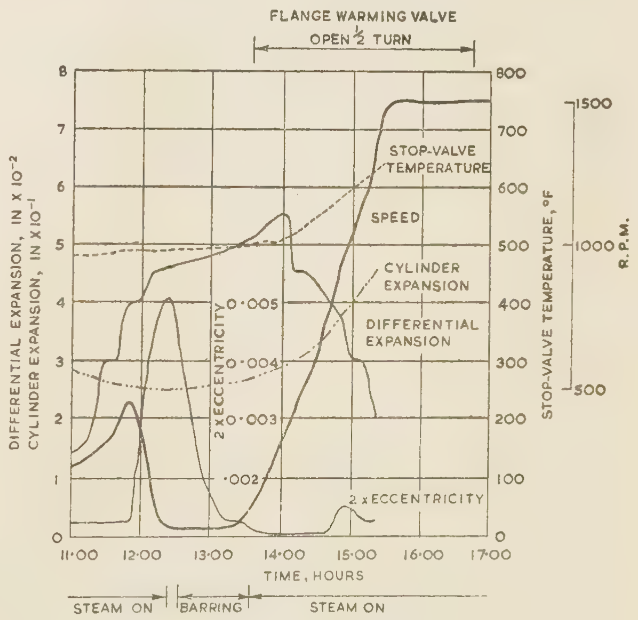

Fig. 6.—Start of 60-MW turbine after 5-day shut-down.

coincidence of a contracting cylinder and bending rotor. Of course, it is possible that the contraction produces sufficient change in alignment for a touch to take place, but it would be expected that such a touch would be cleared in the course of a few starts and the effect would disappear. On the machine under review, provision is made for steam to be passed along a recess between the faces of the horizontal joint flanges. The object is to enable the warming of the cylinder to be accelerated. restraint on the movement of the h.p. bearing pedestal. On examination the movement was found to be irregular, and further investigation revealed that this was probably due to deterioration in alignment of the pedestal keys. When these were restored to their original condition, expansion became regular again.

A typical subsequent run-up after a two-day shut-down is illustrated in Fig. 7. It seems to indicate great caution between

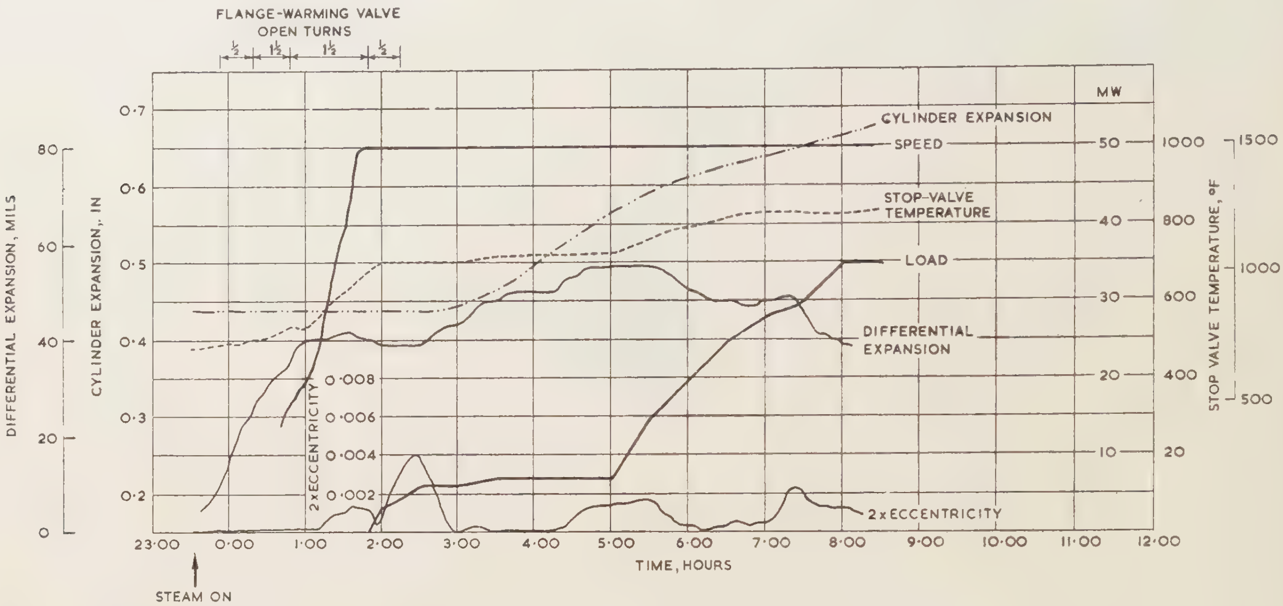

Fig. 7.—Start of 60-MW turbine after 2-day shut-down.

However, it is believed that when the steam supply is colder than the cylinder, it is also advantageous to pass cold steam along the recess in order to bring the metal temperature down to that of the steam as quickly as possible, so that the process of expansion can begin earlier.

Whether or not there is any inherent advantage in this procedure cannot be established from this record (Fig. 6), but it can be used to support the theory that bending occurs when there is rapid heat flow into the rotor. Referring to the record, steam is admitted at 11.00h at a stop-valve temperature of approximately 500° F, and it will be noted that it remains at this temperature until 14.00h. The turbine rotor is undoubtedly warming up from 11.00h onwards, as is shown by the differential expansion record. It is reasonable to suppose that steam is, in fact, entering the inlet end of the turbine at a higher temperature than the metal, almost from the beginning. It does not immediately reverse the cylinder movement, although it expands the rotor, owing to the greater heat capacity of the cylinder and to its greater rate of loss. By 12.00h the cool surfaces en route have been sufficiently heated, and hotter steam is reaching and passing over the gland part of the rotor. The heat flow from this hot steam into the rotor in the region of the glands may be the real cause of the eccentricity. The eccentricity is corrected by reducing the steam flow and thus lowering the temperature of the steam in the glands, rather than by some mechanism directly connected with the reversal of cylinder movement, which occurred about the same time.

The belief that there is some direct connection between a smooth run-up and an expanding condition appears to be widely held, but no theory has been advanced to account for this mechanically. The irregularities in the differential expansion record shown on the chart (Fig. 6) are probably due to

23.30 and 01.00h for reasons not obvious from the chart. From 02.30 to 05.00h the load carried was limited by the boiler. Otherwise the chart presents several exercises in the understanding of the relation of the several curves to each other.

Fig. 8 gives an example where cause and effect seem more clearly related. The machine was practically cold when starting operations commenced at about 09.00h. After a cautious start the rate of heating was accelerated at about 11.00h (by taking on load), but under the prevailing conditions the accelerated rate proved more than the machine would accept, and the rotor developed eccentricity. The corrective was to reduce the rate of heating by greatly reducing the steam flow, dropping all load and even losing speed. The desired effect was rapidly achieved. At about 12.30h the general temperature level was such that speed could be restored, and load accepted again without adverse effects. It is believed that on this occasion turbovisory equipment was the means of drawing attention at a critical time to a condition which might have got out of control if it had been allowed to persist.

In the previous examples eccentricity was increasing at a dangerous rate and somewhat drastic action was necessary. Usually—and especially after a little experience of a machine—only a reduction in the rate of heating is required. This is illustrated by the record shown in Fig. 9.

Fig. 10(*a*) shows an interesting record. Apparently random fluctuations in eccentricity occurred. On examination an h.p. feed-water heater proved to be flooded.

Fig. 10(*b*) shows the effect on eccentricity when full load was thrown off owing to a cable fault. The sudden increase in eccentricity from 0·004in to 0·007in may not be an indication of shaft bending, but possibly an oscillation of the shaft in the bearings following the rapid reduction in torque. It will be

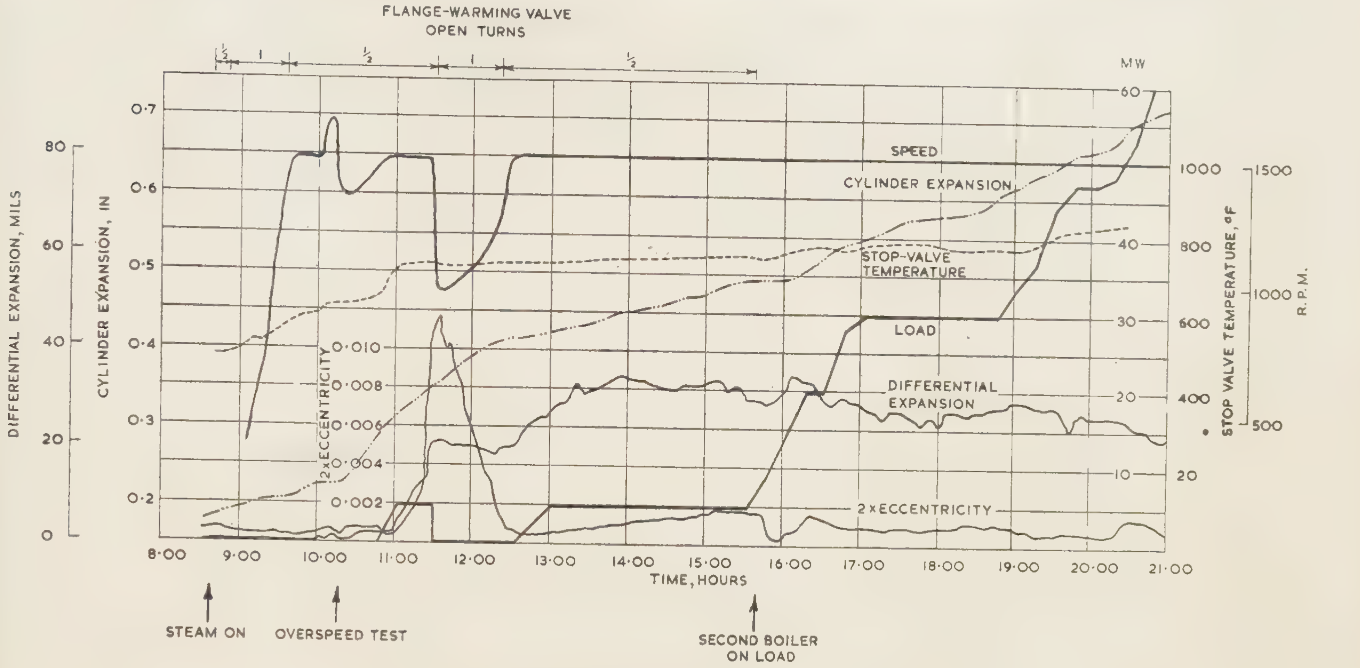

Fig. 8.—Start of 60-MW turbine after 12-day shut-down.

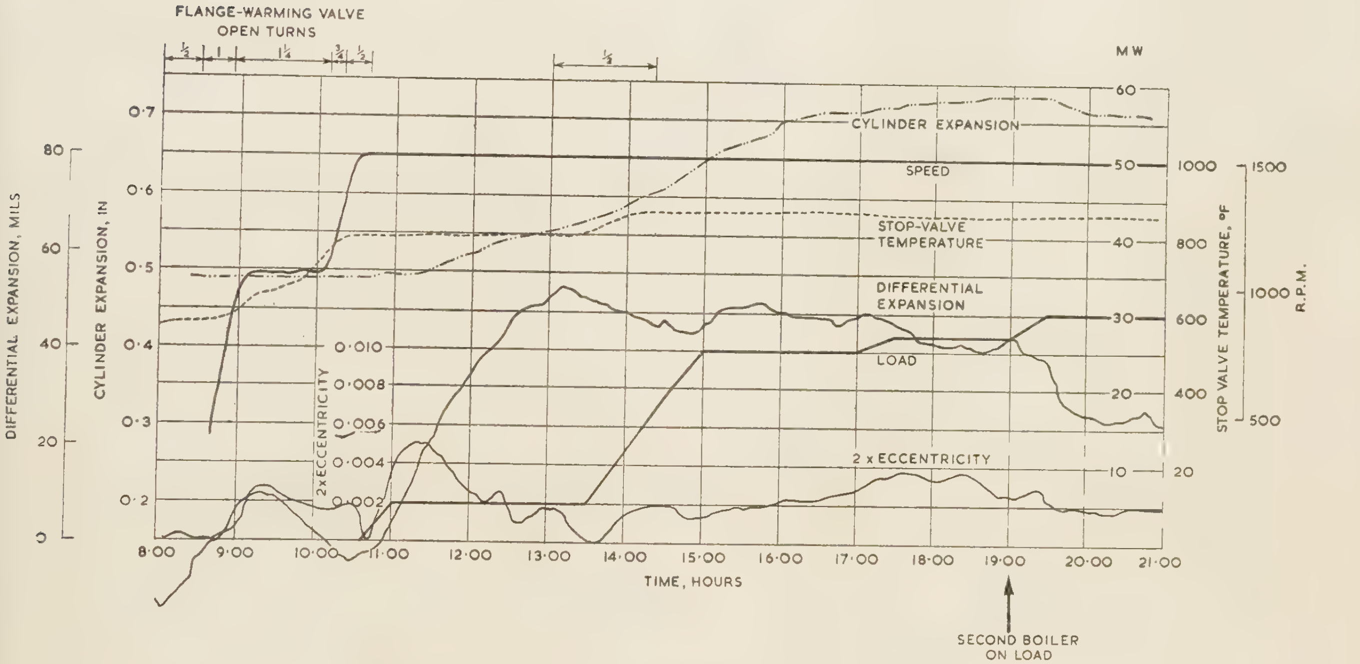

Fig. 9.—Start of 60-MW turbine after 38-hour shut-down.

emembered that the instrument measures horizontal movement nly. Possibly, a temporary bend may be indicated, since sudden loss of load produces a change in the temperature istribution and in the flow of steam through the turbine glands.

The above records cover a period of several years during which he average time for starting the turbine has been considerably educed. Turbovisory equipment may claim to have made an nportant contribution to the improved knowledge which has esulted in this reduction.

(4.2) Three-Cylinder 50-MW Turbine

After more experience had been gained, an opportunity was afforded for making systematic observations, including the steam and metal temperatures, on the starting and running of a 50-MW 3-cylinder machine running at 3 000 r.p.m. The steam conditions were of the order of 900 lb/in^2 and 900° F supplied from a range. Turbovisory equipment showing differential expansion and rotor eccentricity was fitted to the h.p. and i.p. cylinders.

Fig. 11 shows an interesting record of a start after a 34-hour

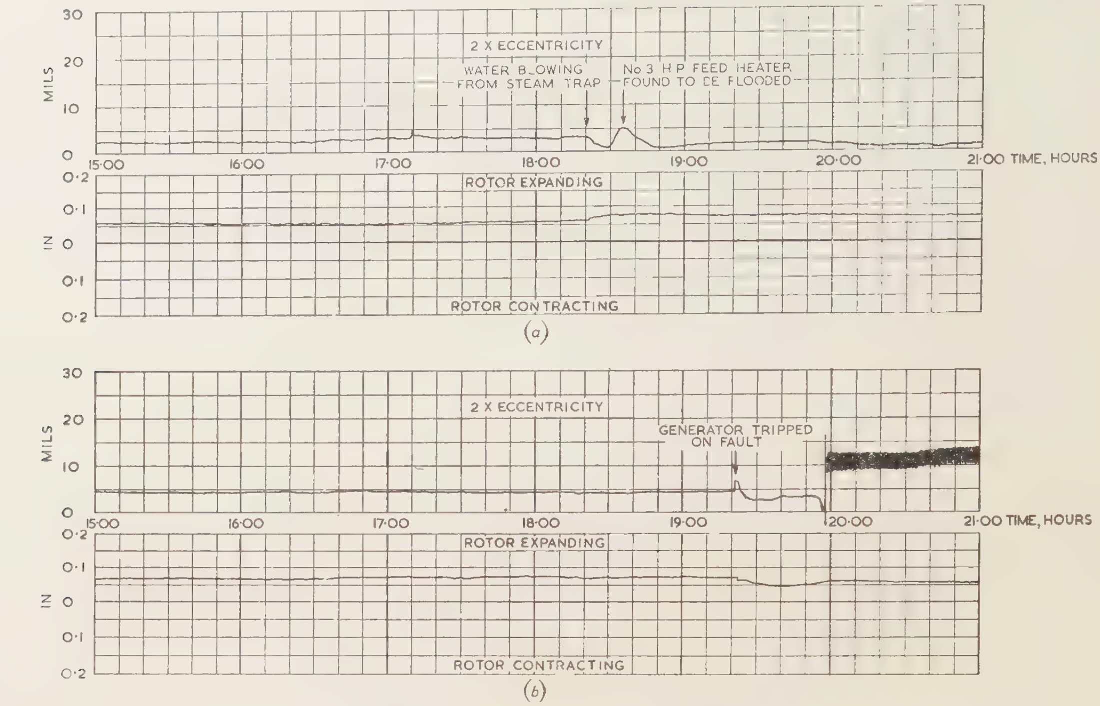

Fig. 10.—Records of 60-MW turbine.

(*a*) Flooded feed-water heater.
(*b*) Generator tripped on fault.

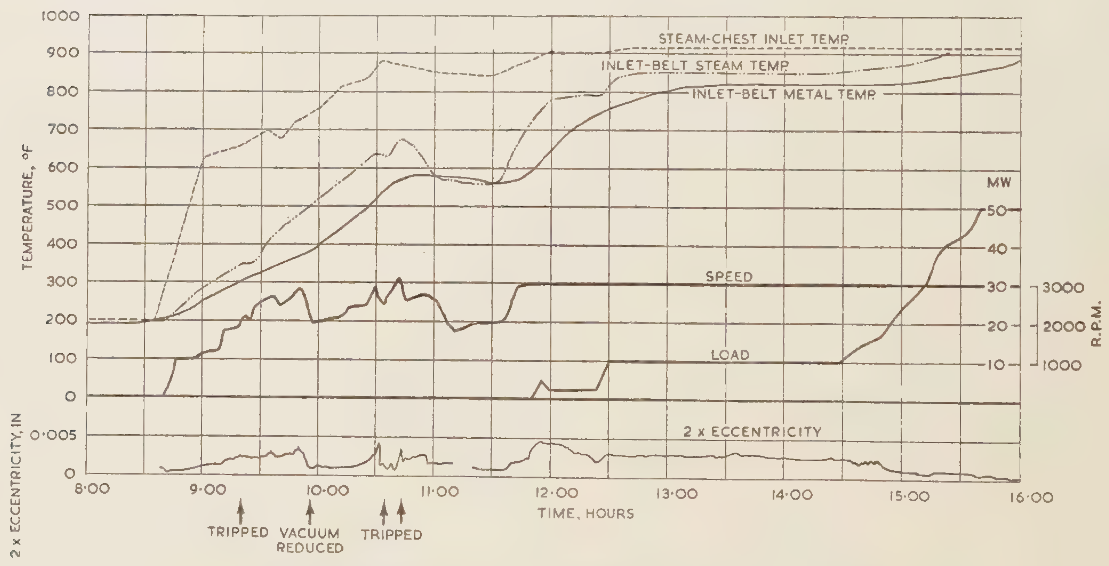

Fig. 11.—Start of 50-MW turbine after 34-hour shut-down.

week-end shut-down. The starting time on this occasion was prolonged in order to allow a number of experiments to be made. With this particular machine, it was found that the rate at which it could be run up and loaded was limited by the onset of vibration of the h.p. rotor. The vibration is due to deflection of the rotor, and the record of its eccentricity therefore becomes the criterion by which running up and loading proceeds. The turbovisory records show the development of deflection before vibration is evident, and at low speeds, deflection is shown long before vibration can be felt. The experiments made during this starting time had the object of finding what conditions caused deflections, with the hope that the reasons would emerge.

Starting at 08.40h with a rotor which the record shows to be substantially straight, there is a fairly steady increase in eccentricity with increasing speed up to about 2 000 r.p.m. The increase in eccentricity may be due to the increased centrifugal forces due to increased speed, but this assumes that, owing to deflection, the rotor was more out of balance initially than it

was believed to be; or it may be due to some other cause whose effect also increases with speed, for example increased steam flow. Another possible cause could be that the spring coupling was holding the driving end of the rotor a little eccentrically. Since the turbovisory magnets are at the opposite end, coupling eccentricity would appear as an eccentricity reading of perhaps one-tenth of its true value at low speeds, but as the speed increased, centrifugal forces would be set up all along the shaft, and the consequent deflection of the rotor would be recorded on the instrument as an increasing eccentricity. To give the coupling an opportunity of readjusting itself, torque was removed by tripping at 09·20h, but it will be seen that no improvement was effected.

The eccentricity continued to increase with increasing speed, and a little before 09·50h it had reached what was considered to be about the maximum that could be allowed. The speed was reduced to 2 000 r.p.m., and the eccentricity greatly diminished; it was better, in fact, than it had been at 2 000 r.p.m. previously. The drop in speed was partly brought about by a reduction in vacuum, which was progressively reduced until about 10·20h with the object of increasing the steam flow without increasing the speed, to see if eccentricity varied with steam flow rather than speed. It will be noted that the eccentricity did not increase. However, there is a qualifying circumstance. It was not realized at the time that one of the steps taken to reduce vacuum would be to allow air to enter the system via the turbine glands. The flow of cool air along the shaft surface may account for the rapid improvement in eccentricity.

At 10.20h normal conditions were restored; hot steam began to flow through the glands, and the vacuum increased. Speed increased, as did the eccentricity—so much so that the set was tripped. Two things will be noted. One is the increase in eccentricity following the change from cold air to hot steam flowing in the outer-gland labyrinth; and the other is the considerable decrease in eccentricity which accompanied the slight reduction in speed after tripping. When full speed was again reached at 10.40h there was a sudden increase in eccentricity, and again it was thought expedient to trip.

Although the mechanism might not be entirely clear, it was apparent that large temperature differences or rapid temperature increases or both were a prime cause of shaft deflection. However, starting a turbine is largely a process of raising the various parts to their working temperature, and temperature must be increased. Also, the danger attendant on a given eccentricity increases with the square of the speed. Thus it was reasonable to experiment by running the turbine steadily at about 2 000 r.p.m. where the eccentricity remained at a safe value, in order to observe whether the corresponding steam flow would produce the desired general rise in temperature level. The striking lesson from this experiment carried out between 11.00h and 11.30h was that it gave no apparent advantage. As there was no increase in general temperature level, there remained no alternative but to increase the steam flow. Some improvement could have been made by reducing the vacuum, but it was clear that the speed must be allowed to increase, and accordingly, at about 11.40h the speed was increased to 3 000 r.p.m. again. The eccentricity remained tolerable. The probable explanation is that at some part of the rotor, where temperature measurements were not being taken, the soaking from 11.00 to 11.30h had raised the temperature sufficiently to ensure a tolerable temperature difference under full-speed steam flow conditions. At 11.50h the records showed that eccentricity, although at a rather high value, was steady, and consequently load was applied. Usually, if the general temperature level is high enough, the effect of applying load is to reduce the eccentricity, but in this example, suitable conditions had not quite been established, and an increase in eccentricity followed the increase in load. The load was reduced and gradually the eccentricity fell. To accelerate the process when it was thought that suitable conditions had been established, the load was increased at 12.30h to 10 MW and then held, as an experiment, at this figure until 14.30h. It was expected that the steam quantity corresponding to this load would be ample to raise temperatures to a stable level with a consequent steady reduction in eccentricity. This expectation was not borne out, but as the loading was progressively increased to maximum between 14.30h and 15.40h, the eccentricity diminished to a negligible amount. There is probably some significance in the irregularity of the eccentricity record between 14.30 and 14.50h. It may indicate either resettling of the coupling springs with increased torque or spasmodic release of restraint on an expanding gland sleeve. At full load and with the turbine thoroughly warm, the rotor returned to its concentric state and ran smoothly, well below the threshold of perceptible vibration.

Nowhere in the record of this start is there any evidence of a rub between moving and stationary parts. Throughout it will be seen that the eccentricity was readily controlled by reducing speed. The rotor, it should be stated, had no critical speed below 3 000 r.p.m.

The start was greatly prolonged in the quest for knowledge, but even allowing for this, it indicates the difficulty, where there is a tendency to transient deflection, of passing sufficient steam to provide a satisfactory rate of heating.

The inlet-belt metal temperature at the beginning of the previous start was about 200°F, and it was not until the metal temperature had reached about 600°F that the rotor began to settle down towards a smooth running condition. It would be expected, then, that if a start was being made with the inlet-belt temperature already at 600°F, no difficulty would be experienced. Fig. 12 shows the record of such a start. The turbine had been shut down for about six hours during the night. No experiments were tried. Gland steam was used freely to maintain the rotor

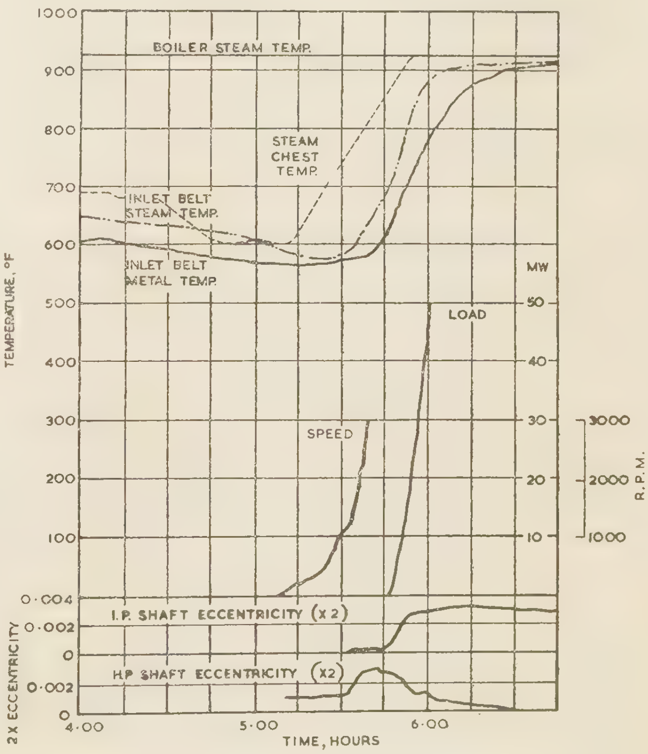

Fig. 12.—Start of 50-MW turbine with warm cylinder.

temperature in the region of the glands. The steam supplied (from a range) was always hotter than the metal. No effort was made to force the start, but it will be seen that rolling began at 05.10h and full load had been accepted by 06.00h. Eccentricity increased a little, but the temperature level was such that the application of load had a salutary effect, and no pause was necessary. The Figure shows the record of the eccentricity of the i.p. rotor as well as that of the h.p. rotor. It is interesting to note that the i.p. rotor developed some eccentricity shortly after the h.p. rotor began to straighten again. It seems likely that the conditions causing deflection were established by an advancing temperature front as the steam flow increased.

It became apparent from a study of the behaviour of this machine under starting conditions that, with this design, significant eccentricity was likely to be experienced if the difference in temperature between the incoming steam at the turbine steam chest and the metal at the inlet end exceeded 250°F.

In the two starts previously described steam was taken from a range, but subsequently special arrangements were made to run the machine as a unit in conjunction with a pair of boilers isolated for this purpose. Figs. 13 and 14 show the record of

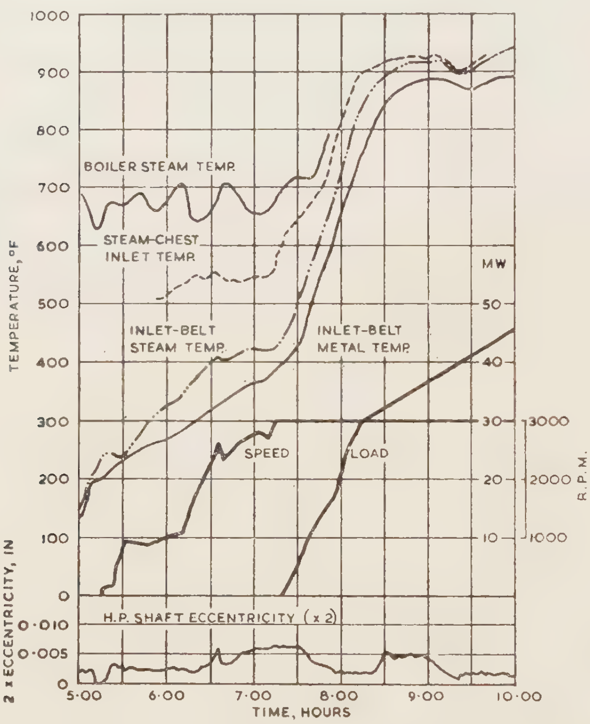

Fig. 13.—Cold start of 50-MW turbine with controlled steam temperature.

the starts made under these unit conditions, but with the boiler steam temperature controlled so that the difference between the turbine stop valve and metal temperature never exceeded 250°F. It will be seen that the starts were rapid and free from difficulty.

(4.3) Three-Cylinder 60-MW Turbine

The value of the permanent record provided by the turbovisory equipment is well illustrated in Fig. 15, where examination of the record disclosed the gradual distortion of a turbine rotor during service. It was the h.p. rotor of a 3-cylinder 60-MW machine, running at 3 000 r.p.m., which had been operating at an inlet temperature approaching 900°F.

Attention was drawn to the rotor through difficulty in starting

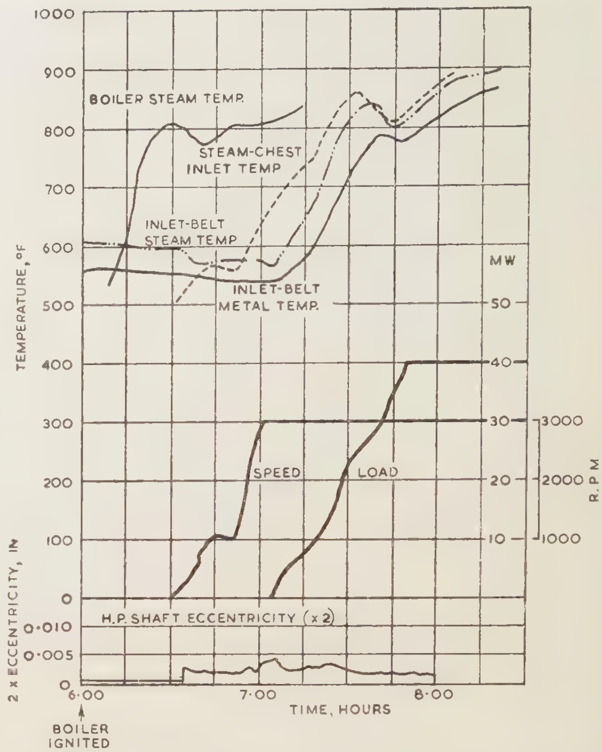

Fig. 14.—Start of 50-MW turbine after 6-hour shut-down; controlled steam temperature.

after the set had been in commercial service for about six months, the turbovisory record showing a rise and fall in eccentricity with increase and decrease in speed, possibly indicating that the rotor was out of balance. Past records were examined, and it was seen that there had been an increase in running eccentricity with time. Although this must have produced a gradual deterioration in balance, it was imperceptible in the running of the set.

Fig. 15(*a*) shows a typical portion of a running record with the set near maximum load, taken soon after commissioning; (*b*) is the record after about two months' operation; and (*c*) after about four months' operation. (*d*) and (*e*) are two starting records, (*d*) at an early stage, and (*e*) three months later.

Table 1

60-MW Turbine—Value of Eccentricity Records

Date	Period of record	Load range	Recorded eccentricity		
			Maximum	Minimum	Average
	h	MW	in	in	in
Initial	24	30–59	0·0025	0·00025	0·001
2 months later	21	35–58	0·003	0·0005	0·002
4 months later	22	58	0·0065	0·002	0·003

Table 1 gives the data obtained from each running record and indicates a progressive increase in eccentricity which if allowed to continue might have led to a breakdown. A steam pipe was removed and the rotor clocked in position, when it was found to be eccentric by 0·0025in. This provokes the thought that it is surprising that a bend which produced no noticeable symptoms at full speed (apart from those shown by the turbovisory equipment) should have caused trouble at lower

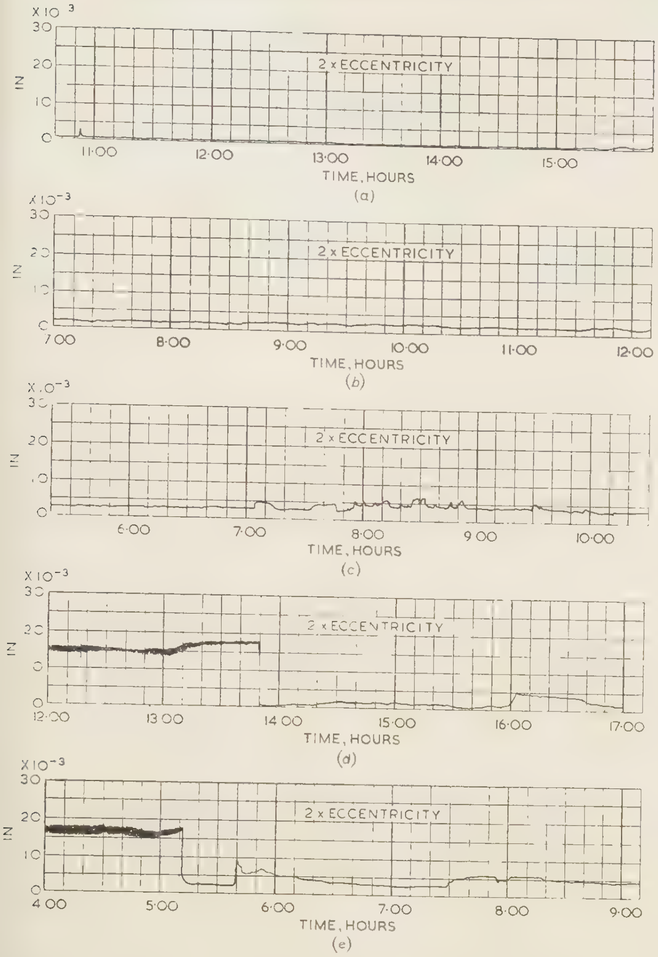

Fig. 15.—Records of 60-MW turbine, showing rotor deterioration.

speeds during running up. It may be significant that the rotor had a critical speed below the running speed. Even taking this into account, it must be concluded that some effect other than lack of balance was present during the run up, and this effect was additive to the permanent bend. The experience also draws attention to the high standard of balance and stability which the use of turbovisory equipment promotes.

(4.4) 15-MW Gas Turbine

Some experience has been gained with turbovisory equipment as an aid to running up a 15-MW gas-turbine installation. This turbine consists of an l.p. and an h.p. unit, the l.p. unit being coupled direct to the alternator and run at 3 000 r.p.m., whilst the speed of the h.p. unit varies with the load. Turbovisory equipment is fitted to each unit. The turbine rotors and cylinders are made of different materials, the rotors being ferritic forgings and the cylinders austenitic castings; the coefficient of expansion of the cylinder material is thus some 50% greater than that of the rotor. In addition, the rotor is cooled by air bled from the compressor air ducting, and the combined effect is to give a much greater relative movement between rotor and cylinder than in a steam turbine. The rotor contracts relative to the cylinder, and thus the differential expansion indicator becomes a much more important feature than in the case of steam turbines.

The set was originally run up to speed on the basis of gas-metal temperature difference. Thermocouples were peened in to the turbine cylinders around the inlets to give the metal temperature, the gas temperature being measured by thermocouples at the turbine inlet. A temperature difference not exceeding 100°C between gas and metal was the criterion by which heat transfer was regulated in order to avoid thermal shock on the austenitic turbine casings.

Both units were run up to speed by means of a hand throttle in the fuel feed to the appropriate combustion chamber. After a small opening of either throttle, it was the practice to allow conditions to stabilize until the metal temperature rose to within 100°C of that of the gas stream, before continuing the heating process. To illustrate this method Fig. 16(*a*) as recorded on the l.p. unit shows a relatively slow and uniform rate of differential contraction; there is a disturbance, however, at the point where the reheat combustion chamber was ignited. The run-up time was 1h 32min, and a further 1h 15min was needed to reach a load of 6 MW.

The latest method is to use the turbovisory equipment throughout the starting and loading cycle. The aim has been to reduce

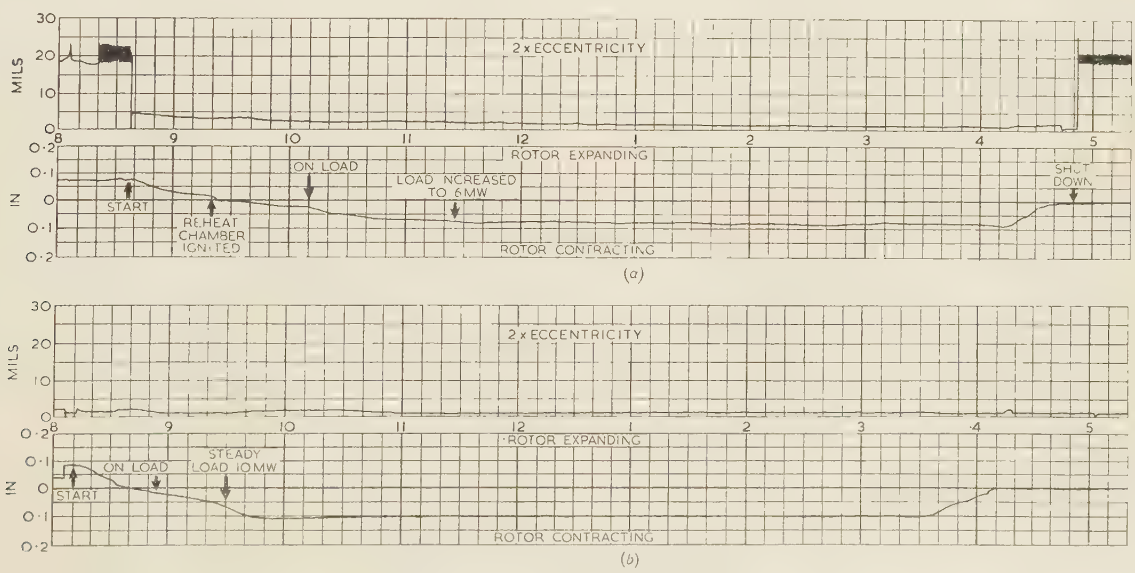

Fig. 16.—Differential-expansion records of 15-MW gas turbine as an aid to starting.

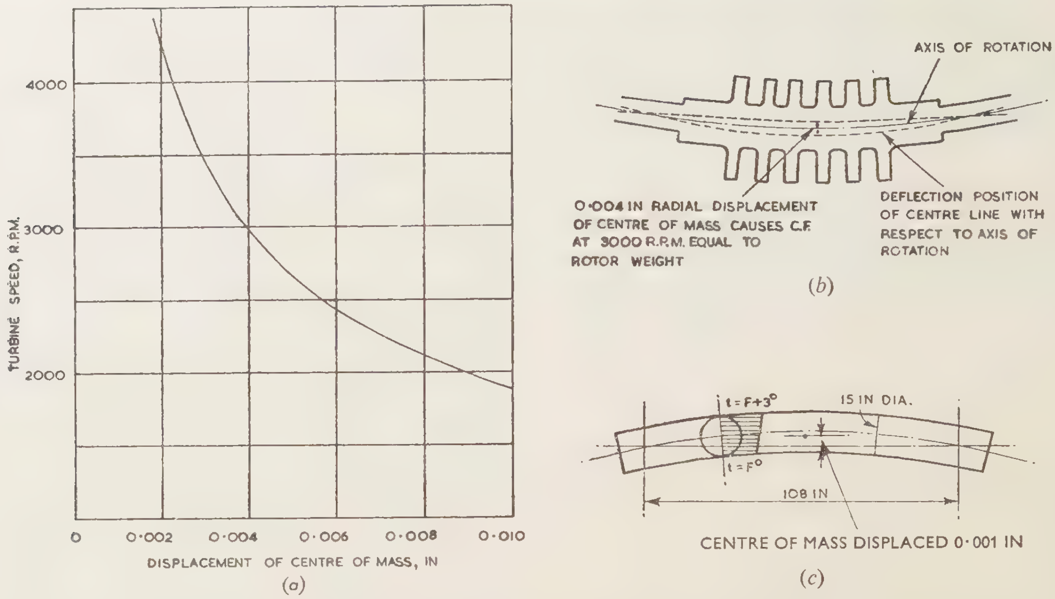

Fig. 17.—Transverse temperature gradient, radial displacement and centrifugal force of turbine rotors.

(*a*) Speed for centrifugal force to equal weight of shaft.
(*b*) Radical displacement of centre of mass.
(*c*) Effect of transverse temperature gradient.

the time taken and hence to reduce the quantity of fuel used when the set is, of necessity, running at a low efficiency. The hand throttles are opened at such a rate as to give a uniform predetermined rate of movement on the turbovisory expansion chart. This method of running up is shown in Fig. 16(*b*), taken from the l.p. unit, from which it will be seen that the time taken before going on load has now been reduced to 34 min and the additional time taken to reach a load of 10 MW has been reduced to 37 min. Reference to this chart shows that after a steady load was reached the rotor continued to contract relative to the cylinder at a diminishing rate for a further 20 min, but no ill effects are shown on the eccentricity chart alongside.

(5) INTERPRETATION OF ECCENTRICITY READINGS

The eccentricity indicator is especially useful because it shows the development of eccentricity before vibration becomes noticeable. The effect of eccentricity is, of course, to displace the centre of mass of the rotor from the axis of rotation, and it is the amount of this displacement which is the primary concern. As previously described, turbovisory equipment in current use does not measure the mass displacement directly; it is more convenient to take the measurement on the shaft outside the steam space. This is a good position from the point of view of the electrical coils and wiring, but it does raise difficulties in the interpretation of the readings obtained.

The obvious approach to interpretation is to assume that normally the shaft runs with its geometric axis and its centre of mass coincident with the axis of rotation. This axis of rotation is determined by the position of the journals in the bearings, and the gravitational deflection of the shaft. When the rotor deflects, the first assumption must be that the deflection is in one diametral plane only, and that it diminishes to zero at the centre line of each journal, where the position in the bearing remains unchanged. Outside the journals the deflection is opposite in phase to that between the journals. If it is further assumed that the curvature between the bearing centres is constant, and the portions at the ends are tangential at the bearing centre lines, it is easy to obtain the relation between indicated eccentricity and radial displacement of the centre of mass.

It may be useful to recall the order of the quantities under discussion. For instance, Fig. 17(*a*) shows the radial displacement of the centre of mass which would produce a centrifugal force equal to the weight of the rotor. At 3 000 r.p.m. the required displacement is about 0·004 in. This is shown pictorially in Fig. 17(*b*). Fig. 17(*c*) shows how easily the displacement can be produced by a relatively small temperature difference. It illustrates a rotor, about 9 ft between bearing centres, having a shaft diameter of 15 in, in which there is a temperature gradient of only 3° F across a diametral plane for the whole length of the rotor, which may be operating at temperatures up to 900° F or more. As a consequence the rotor deflects 0·001 in between the bearings. To measure these deflections, a reading is taken outside the bearings. Based on the assumptions previously made, the indicated reading will be about one-half to one-third of the displacement of the centre of mass, for a rotor of normal proportions. (The actual reading shown on the instrument must be divided by two to give the eccentricity or displacement.) If it is postulated that a centrifugal force must not exceed half the weight of the rotor, the centre of mass deflection must not exceed 0·002 in and the reading on the instrument must therefore not exceed 0·001 in eccentricity, or 0·002 in as indicated. For 1 500-r.p.m. machines these figures must be multiplied by four.

When turbovisory equipment was first installed, efforts were made to keep well within this figure. However, experience has shown that rotors run satisfactorily with higher readings. Even at an eccentricity reading of 0·005 in at full speed, there is no serious roughness, although sometimes a little vibration is noticeable.

Where deflections arise from thermal causes, the most severe curvature may be in the glands, near the bearings, thus giving a deflection curve which exaggerates the reading and reduces the effective displacement. The deflection may not be entirely in one plane, or it may be complex so that there is no relation between the reading and effective displacement. Of course, a complex curve could have the opposite effect and result in a reading which was low and misleading. In view of several experiences where the turbovisory equipment has obviously over-estimated the effective deflection, it is a curious and

important fact that no instance of the turbovisory reading underestimating the effective bend has been observed so far.

The largest eccentricity readings associated with smooth running are found in the intermediate rotors of three-cylinder machines, where the three rotors and the generator are in line; there are spring-type flexible couplings between the h.p., i.p. and l.p. rotors. The i.p. eccentricity detector magnets are at the inlet end between the spring coupling and the first bearing of the i.p. rotor. Indicated readings of i.p. rotor eccentricity of over 0·010in have been observed in several instances, with negligible accompanying vibration.

One rather interesting suggestion was that since turbovisory equipment was sensitive to eccentricity but not to frequency, the large eccentricity might be explained by that shaft following an eccentric path at a lower cyclic frequency than the speed of rotation. The turbovisory equipment allows such a lower frequency to be detected. Accordingly tests have been made, but so far no low-frequency cycle has been discovered. In considering these problems it should be noted that bearing clearances are always large compared with any tolerable eccentricity.

Work is proceeding on the problems outlined in the foregoing, but it seems important to recognize that at the present time the eccentricity indication of turbovisory equipment should be read in conjunction with the known experience of any particular machine.

Experience will be built up gradually, with machines under careful observation. Having once established the characteristics of a machine, operational routine will be developed to suit, using the turbovisory readings as a guide. Any deviation from the normal readings for a given condition will have careful consideration. It may indicate some abnormality developing and give the great advantage of enabling plans for attention to be made well in advance.

(6) USE OF READINGS AS AN AID TO OPERATION

When considering the use of turbovisory equipment as an aid to starting, it will be seen that the two indications which enable control to be exercised are those of eccentricity and differential expansion.

(6.1) Temporary Deflection (Eccentricity)

It will be useful to discuss some of the causes of deflection.

(*a*) *Stationary rotor lying in a hot cylinder.*—These conditions apply just prior to starting after, say, a night's shut-down. The temperature in vertical transverse places in the hot cylinder of a turbine at rest is rarely uniform, and consequently the rotor lies in a transverse temperature gradient and bends accordingly, usually convex upwards. This state of affairs is immediately shown on the turbovisory record when slow turning begins. The slow turning period must be long enough to allow the rotor to straighten before the run-up. Otherwise it will deflect still more under the influence of the unbalanced centrifugal force until it rubs against stationary elements, and in consequence becomes overheated locally and so permanently distorted. It is of the utmost importance that a rotor is straight within close limits before it is run up to speed.

Formerly the perception of the turbine driver was the only safeguard against running up with a bent rotor, and tribute must be paid to the high tradition of competence which has been established, but the turbovisory equipment now gives a warning well before vibration indicates approaching danger.

Although turbovisory equipment in one or other of its settings shows if a rotor is bent, it usually records readings taken in a horizontal plane. The bending of a stationary rotor in a hot cylinder has been accurately observed by means of a dial micrometer with vertical extension rod bearing on the shaft. Fig. 18

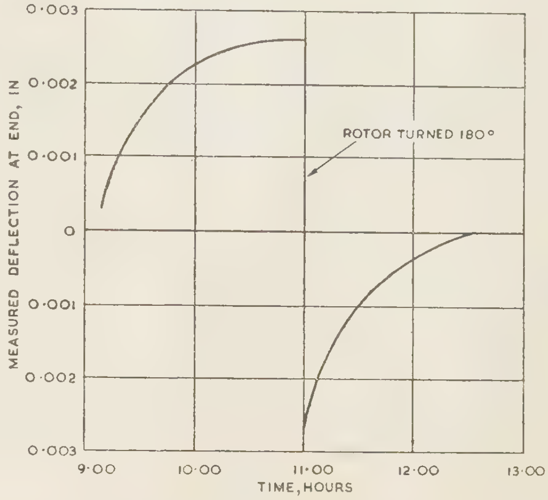

Fig. 18.—Bending of stationary rotor immediately after shut-down.

shows the readings noted on such an instrument for a period after stopping the rotor. It will be seen that the rotor bent upwards between bearings. After two hours of upward bending, the rotor was turned through 180° and the bend was corrected, as would be expected.

In machines without turning gear it has been noted that it is sometimes difficult to re-start after a short shut-down, whereas after a prolonged shut-down there is no such difficulty. The explanation is clearly that after a short shut-down the temperature level is high and temperature gradients correspondingly large, and hence the stationary rotor is bent more than after a long shut-down. The greater bend requires longer slow running for its removal.

Since the temperature gradient almost certainly starts in the cylinder and is transmitted to the rotor, liability to this kind of bending depends on factors such as the completeness of lagging and the existence of hot or cold air streams around the machine.

(*b*) *Temporary thermal gradients developing in transverse sections of the rotor even when it is rotating.*—These arise from non-uniform heat flow into the rotor. Probably the most general cause of such non-uniform heat flow is a gland sleeve which is much hotter than the shaft, and owing to differential expansion, is making contact only along a line. Heat flow into the shaft is most rapid along this line. Section 7 describes an experiment showing how bending takes place under these conditions. A gland sleeve will become much hotter than the shaft when the steam supply is much hotter than the turbine, and the mass of steam flowing is sufficient for rapid heating to take place.

Temporary bending of this type may occur at any speed, and its early detection is an invaluable service of the turbovisory equipment. When it does occur the remedy is to reduce the steam flow, and consequently the speed, until the condition has corrected itself.

Where a rotor runs above its critical speed, it is particularly important to note that there is no appreciable bend when the speed has reached 1–200 r.p.m. below the critical speed. When it is observed from the turbovisory indicator that the rotor is straight it should be taken quickly through its critical speed.

It will be found that as temperatures approach the working level, or whenever steam and metal temperatures approach within, say, 150°F of each other, the tendency to deflection disappears. Until this condition has been attained, the eccentricity indicator should receive careful attention.

Other possible causes of non-uniform heat flow into or out

of the shaft are uneven discoloration of the rotor surface, or splashes of water impinging on the rotor.

(*c*) *Non-uniform restraint on the differential expansion of sleeves with respect to the shaft.*—Temporary deflection due to this cause may persist to some extent under rapid starting conditions during the mature life of the machine, but usually the effect is most pronounced during early life and accounts for some of the "teething" troubles.

It is believed that temporary deflections as described under (*a*) and (*b*) above are the main causes of permanently bent shafts. Accidental contact between fixed and moving parts, i.e. a rub, is an essential feature in the mechanism producing a permanent bend. The indication of the turbovisory equipment enables bending to be detected and corrective measures applied, in ample time to avoid a rub. A rub can occur from causes other than the temporary bending of the rotor and will, of course, first cause a temporary deflection which, if allowed to persist, will lead to a permanent bend.

(6.2) **Rubbing**

Rubbing may be caused by distortion of the cylinder. It is probable that all cylinders distort a little as the temperature increases or as temperature conditions change, but in the early life of the machine, clearances will accommodate themselves to suit; and thereafter no effect on the rotor, and hence on the running, will be apparent. However, exceptional circumstances may produce exceptional distortions at any time; one such circumstance is the sudden entry of water with the steam.

The rotor may be unaffected thermally, but nevertheless may run eccentric with consequent bending due to centrifugal forces. This could be due to faulty coupling alignment.

Turbovisory equipment detects bending or eccentric running of whatever type. Up to the present there has been no instance where it has underestimated the gravity of a situation.

(6.3) **Differential Expansion**

Most turbines are designed with axial clearances of 0·060 to 0·100in on the inlet side of the rotor blades and 0·2 to 0·3in on the outlet side.

Where the rotor has a much smaller mass than the cylinder, the rotor rises in temperature during starting much more rapidly than the cylinder and even the large back clearance may be taken up by its more rapid expansion. To avoid this, heavy cylinders are often provided with means for heating the heavy horizontal joint flanges independently of the steam flow through the blading. The cylinder is thus enabled to keep in line with the rotor.

The reverse effect, although much less marked, occurs on stopping, and here there is the additional danger that air may be drawn in through the glands and cause rapid contraction of the rotor.

All these effects are readily detected by the differential expansion equipment. Fig. 19 is self-explanatory and shows how differential expansion may be controlled.

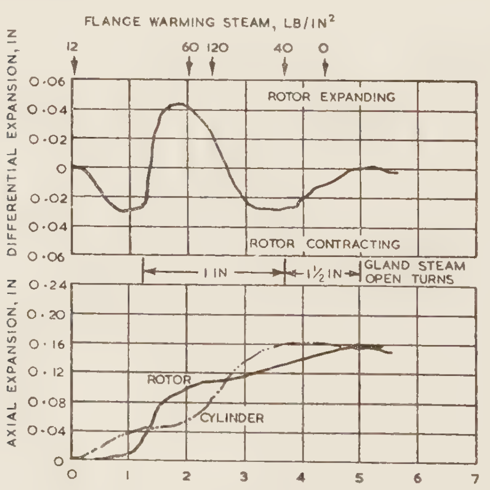

Fig. 19.—Changes in differential expansion; cylinder warming prior to starting.

(7) THE USE OF READINGS AS AN AID TO DESIGN

Turbovisory equipment subjects a number of characteristics of steam-turbine behaviour to continuous scrutiny. Rotor bending, for instance, which was previously significant only to the extent of the impression made on the operator by the resulting vibration, is now measured and placed on record, and inquiry into the reasons for certain characteristics of behaviour has been greatly stimulated. One of a number of studies which are now in progress may be taken as an illustration.

During the course of a run-up, a rotor which has been started in a straight condition often temporarily deflects. This transient bending is recorded and studied in relation to the starting procedure. Such a study has led to the conclusion that some transient bends originate in the gland portion of the rotor, and it has been suggested that during periods of large temperature difference between the outside of a gland sleeve (where hot steam is passing) and the shaft inside the gland sleeve, heat flow from sleeve to shaft is significantly non-uniform and produces transverse temperature gradients in the shaft.

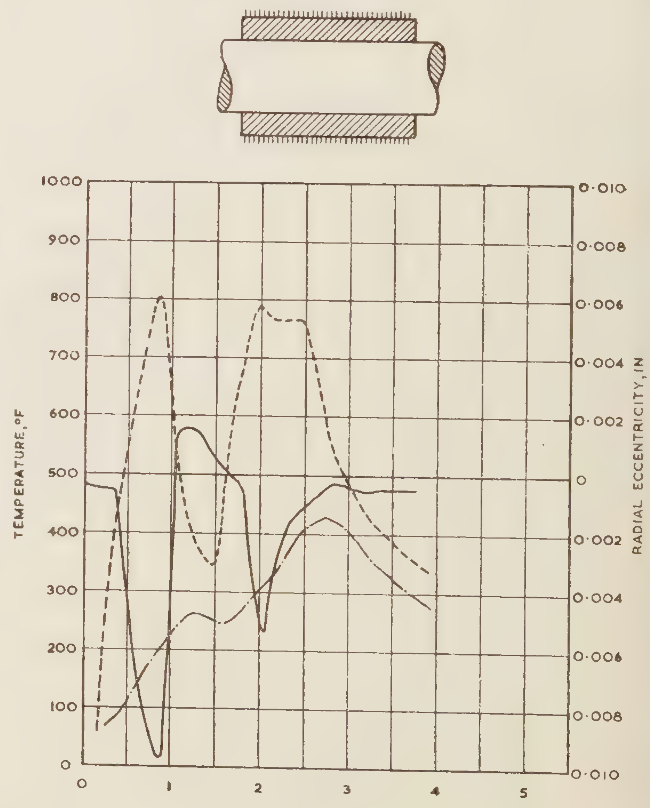

Fig. 20.—Influence of gland sleeves; original design.

——— Radial eccentricity, clock, between wheels 2 and 3.
- - - - - Temperature of main gland, $\frac{9}{16}$in from surface.
·—·—·— Temperature of bore under balance gland.

This theory was tested experimentally. A rotor was slung in a lathe, and a small oven was built round the gland portion. Thermocouples were placed in the sleeve and at the centre of the shaft. The sleeve was heated while the rotor was rotated slowly. A dial micrometer bearing against the shaft registered any bend which took place. The first sleeve to be tested was the usual design which makes continuous contact with the shaft over the whole of its inner surface. Fig. 20 shows how the temperatures in both the sleeve and shaft changed; it also shows how the shaft bent. It will be observed that the bend is closely related to the temperature difference between sleeve and shaft, and that when this difference falls sufficiently the rotor becomes straight again. The record suggests that no bending occurs until the sleeve temperature is above that of the shaft by an amount which causes the original shrink fit to be lost by thermal expansion. Line contact then occurs, and the consequent more rapid flow along this line explains the development of transverse thermal gradients.

(8) CURRENT DEVELOPMENTS

So far only two measurements have been discussed; subsequent experience has indicated that the other readings may be of value, and it is proposed to incorporate these additional measurements on many of the new equipments at present being manufactured.

(8.1) Additional Measurements

The following additional readings have been considered and apparatus has been designed to provide the measurements:

(*a*) *Speed and Kilowatt Output.*

Examination of the various turbovisory records has always meant a check on the speed and kilowatt output of the set at the relevant times. These two readings have accordingly been incorporated in the records so that during any subsequent examination of the charts full relevant information is available for analysis.

(*b*) *Steam/Metal Differential Temperature.*

Although turbines can only be heated by means of a temperature difference between steam and metal, a small temperature difference appears to give the most reliable assurance of smooth starting. Thus an optimum temperature difference tends to be established, dependent upon the particular turbine and the starting rate desired. An indication of selected temperature difference is therefore valuable.

(*c*) *Overall Expansion.*

Many operating engineers have concluded that turbines should not be run-up whilst they are in contracting condition. Since the cooling time of a turbine is considerable, it will be appreciated that this movement must be measured accurately if the earliest possible start is to be made—in other words, the exact time when a turbine changes from contracting to expanding is considered to be an essential piece of information.

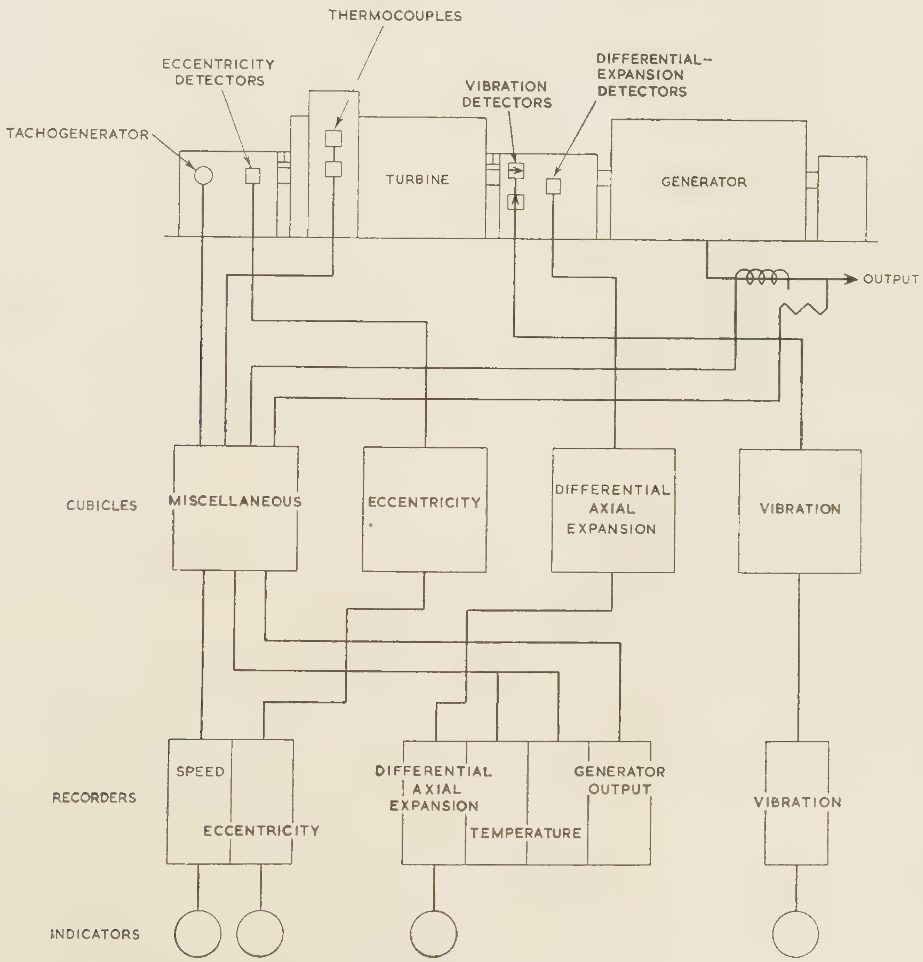

Fig. 21.—Complete turbovisory equipment.

(*d*) *Vibration.*

Whilst it is generally accepted that the measurement of eccentricity already described gives preliminary warning of vibration, there are a number of operating engineers who consider that the measurement of vibration is extremely valuable, since apart from shaft distortion it can indicate and record incipient bearing trouble.

(*e*) *Valve Positions.*

Whilst these are not normally indicated, this information can be suitably presented if considered desirable.

(8.2) Description of Vibration Equipment

The vibration detector consists of a mass of soft iron, suspended on flat springs between the pole faces of a U-shaped laminated core, so that it is free to move in one direction of the horizontal plane. A small permanent magnet is fixed to the base of the detector, and the magnetic circuit is completed through the soft-iron mass and through the laminated core. Search coils are wound on the fixed laminated core. If the base of the detector is fixed to a vibrating surface it will vibrate, but the suspended mass will remain in one position, providing that the frequency of vibration is not the same as the resonant frequency of the seismic mass.

The relative movement between the soft iron and the laminated core causes induced voltage to appear across the search coils. These voltages are proportional to the displacement of the base of the detector relative to the seismic mass, and hence to the amplitude of vibration of the base upon which the detector is set.

An amplifier unit which can be adjusted to the correct gain, by using an independent calibrating signal on the input, is connected in turn to a series of these detector units. Hence each bearing can be examined in turn for in-line and transverse vibration.

(9) SUGGESTED PRACTICAL TURBOVISORY EQUIPMENT

Fig. 21 shows a modern turbovisory equipment, based on experience gained over the past few years. It consists of two or three separate recorders all synchronized and supplemented by suitable indicators where they are considered necessary.

The first recorder gives two separate and continuous traces, one of eccentricity and the other of speed, each reading being duplicated by suitable indicators. Since these quantities are important and quick moving, continuous records are considered essential.

The second recorder is of the intermittent multi-trace type and gives indications at intervals of 5 or 15sec. This will record the differential expansion, the generator kilowatt output and any temperatures which may be required. Since all these quantities are slow-moving, the intermittent nature of the record is no drawback. Suitable indicators may be added.

If vibration measurements are required, another intermittent multi-trace recorder may be used, coupled through a suitable automatic switch which selects each seismographic head in turn, to give a record of its vibration output.

Periodic checks of the chart will serve to indicate incipient trouble. A continuous record of any point can be selected by means of a special switch.

(10) ACKNOWLEDGMENTS

In conclusion, the authors wish to thank Mr. A. R. Cooper, the Controller, North Western Division, British Electricity Authority, Mr. Norman Elce and Mr. H. West, Metropolitan-Vickers Electrical Co., Ltd., for permission to publish the paper. They also wish to acknowledge the generous help given by many of their colleagues, particularly Mr. W. Davies and Mr. J. Whitfield, who have contributed much information on running experiences with large steam turbines.

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[The discussion on the above paper will be found on the next page.]

DISCUSSION ON THE ABOVE TWO PAPERS BEFORE THE SUPPLY SECTION AND THE STEAM GROUP OF THE INSTITUTION OF MECHANICAL ENGINEERS, 24TH NOVEMBER, 1954

Mr. F. Shakeshaft: I am sure that we shall all wish to congratulate the authors of these two papers, which deal with important problems associated with the safe operation and new design features of large plants using extra high pressure and temperature steam cycles. They jointly cover research and field work over the past 12 years.

In 1942, Mr. Karl Baumann approached the late Sir Johnstone Wright for assistance in procuring thermionic valves, condensers, inductances, etc., by means of which to construct the first British turbovisory gear. Somewhat protracted negotiations with the departments of the ministry concerned were necessary before this material could be obtained for use in the manufacturing and electricity supply industries. At that date Mr. Baumann forecast that nearly a decade would elapse before the gear would be perfected and the full benefits accrue in respect of safe operation and the evolution of advanced designs for machines in the 100–200 MW capacity range. A study of the papers confirms this view, but in the meantime its wide adoption has enabled the safe commissioning of plant with a power of over 4½ million kW, and it has probably saved several million pounds sterling by the avoidance of enforced outages and costly repairs. As even the suggested practical and extended turbovisory equipment can be installed at considerably less than 1% of the turbine plant cost, or about that involved in little more than one day's outage of a large plant, I am sure it will be agreed that the provision of such gear is a cheap insurance.

We have not reached finality in the development of this equipment, and as is already contemplated by one manufacturer, I suggest that the cubicle gear be so packaged as to enable it to be incorporated in (*a*) stations already designed to have separate boiler and turbine control panels, (*b*) those designed to use a combined boiler and turbine control panel, and (*c*) future centralized control rooms. Such a policy would expedite the manufacture, erection and commissioning of plant.

In view of the fact that during the next four years the B.E.A. are to commission some 100 sets of 60 MW capacity in the 900 lb/in², 900° F class, and about 40 sets in the 100–120 MW class, using steam at a pressure of 1 500 lb/in² and temperatures of 1 000–1 050° F, including reheat, I would make the strong recommendation that overall expansion gear be also included in the equipment, and would also suggest that the other equipment should have the following order of importance (the first four items are mechanical):

(i) Overall expansion.
(ii) Axial clearances.
(iii) Eccentricity.
(iv) Steam/metal temperatures.
(v) Pedestal vibration.
(vi) Speed and kilowatt output.
(vii) Valve positions.

With regard to overall expansion gear, many of the 140 sets will be of the 3-cylinder type, some being reheat sets with triple exhausts. The full expansion will therefore range from about 0·75 in to over 1 in from the cold to the hot state. Moreover, quite a number have separate thrust blocks for each cylinder and flexible couplings between h.p. and i.p., i.p. and l.p., and l.p. generator spindles. Experience indicates that if the spindles heat more rapidly than the casings there is a distinct danger of "coupling lock," especially in large-capacity sets with their associated high torques. This has resulted in the h.p. thrust taking all the load, and has even caused heavy wear on the surge pads of the i.p. and l.p. thrust bearings. Records show that, within a few days, wear of up to 0·080 in has been scoured from the surge-pad surfaces. The loading of a machine with the casings undergoing contraction also aggravates such troubles, and the provision of overall expansion gear therefore assists the turbine driver to avoid dangerous starting and loading conditions.

Overall expansion gear is also useful to the driver in giving a continuous recording of the outer pedestal movement and indicating whether or not any stricture has developed owing to the roughening of guide keys, etc. In the United States the General Electric Company are now fitting rows of bronze pads in the sole plate, which are lubricated with a non-carbonizing material.

To avoid casing distortion on nozzle-governed sets, which results in malalignment, Westinghouse and Allis Chalmers arrange that all valves are lifted simultaneously during the starting period. Steps are also being taken to prevent the impingement of hot gland-leakage steam on pedestal walls, which has caused misalignment in a vertical plane containing the axis of the sets.

Axial clearances can be more accurately interpreted when (i) overall-expansion and (iv) steam/metal temperature readings are available. Consideration might also be given to the provision of gear to indicate any possible leakage through steam-to-gland control valves, or alternatively to the use of two valves in series.

With regard to eccentricity, the lucid explanations given in Sections 1, 5, 6 and 7 of the paper by Messrs. Ashworth, Hall and Gray on the causes, operational correction and design methods to control transient deflection are worthy of close study. On no account must these transient deflections assume such a magnitude that they result in rubbing, otherwise a bent spindle is inevitable.

The following observations are submitted for further consideration. First, to prevent the ingress of water under starting conditions the superheater and pipe line should be drained by dumping for as long as is necessary, at a point adjacent to the stop and emergency valves of the turbine. After condensing, this wet mixture would be sent to separate tanks, where it could be re-evaporated at leisure before reintroduction in the water-steam loop.

Secondly, all large unit sets should be provided with pressure governors to reduce the turbine load in the event of coal sticking in the boiler chutes. Experience indicated that prior to fitting such a device the pressure fell by over 7%, and the temperature by 150–200° F in 5 sec, from such a cause. It was established that blade breakage, partially attributable to water carry-over, had occurred.

Thirdly, as transient deflection can be caused by even small transverse temperature differences, consideration should be given to exploring the thermal conductivity of rotors of either drum or monobloc construction. Dr. Sykes has found that carbides can vary the thermal conductivity in the ratio of nearly 2 : 1.

Fourthly, investigation into the causes of oscillation of the rotor journals in the oil film of the bearings, which would be registered as eccentricity, is taking place. Nozzle-governed machines which must use partial and variable admission are more prone to this trouble and are receiving great attention in the United States with a view to its ultimate elimination. It would also appear that variations in oil viscosity can aggravate the trouble.

(v) Pedestal vibration, (vi) speed and kilowatt output, and (vii) valve positions, call for no special comment, as they are mainly useful in augmenting the data outlined in (i) to (iv). It would, however, be useful for the speed-recording gear to be provided with a special instrument which could graphically record the rate of increase of speed after the trip bolt has functioned.

Mr. F. J. Hutchinson: Turbovisory gear is one link in the chain of operational development which is forced into being by the increases in pressure and temperature associated with the large units now being designed and coming into operation. Its essential purpose is to enable critical particulars regarding the behaviour of a turbine, when being started up in the shortest possible time, to be continuously and easily under observation and review. As such it forms one part only of a chain of critical particulars, which must be kept under observation when a large boiler-turbine unit is started up, and which are together known as "instrumentation."

"Instrumentation" can be divided broadly into two parts. One part applies to the requirements of the unit in relation to output; and the other relates to the safety of the equipment and can be regarded as "protective instrumentation." In large modern power stations which are equipped with boiler-turbine units operating with high initial thermal conditions, the "instrumentation" is primarily of the chart-recorder type, and the necessary indicating instruments take their impulses from the recorders. Thus there is a tendency for the recorder charts to replace the traditional log sheets. Figures of less than one-half a man per kilowatt installed constitute the whole personnel of such a station, but more men are employed in maintaining the instruments in working order than are ever employed at any one time in using the instruments to run the unit.

In Section 4.1 of the paper by Messrs. Ashworth, Hall and Gray, it is stated that the spindle of a 60 MW machine bent when low-temperature steam was admitted on starting up. Is there any record of the differential temperature between the steam and the turbine casing? Would the position have been eased if the rotor had been barring at, say, 100 r.p.m. instead of probably 20 r.p.m.? Figs. 7, 8, and 9, show rates of loading which are remarkable for their moderation; they vary from 9 min/MW to 3 min/MW. Is there any reason for this, since, in general, loading rates of from 1 to $2\frac{1}{2}$ MW/min can normally be achieved?

These authors comment on the robustness of the modern impulse turbine. Have they performed any investigations on supervisory gear related to turbines which are not predominantly of the impulse type?

In Section 8.1 of this paper, it is indicated that additional measurements could, with advantage, be provided, and the authors would, no doubt, be the first to agree that for a progressive outlook the purely turbine supervisory gear must be supported by equally critical temperature measurements related to the top and bottom of the boiler drum, the metal of the primary superheater, and the gas in the first passes of the boiler, etc. Without these the story is not complete.

Mr. G. R. Peterson: The first obvious reason for the use of this type of equipment is safety in starting machines. It is extraordinary that for so many years we have left a driver in charge of a machine, the value of which may be several hundreds of thousands of pounds sterling, and provided him with practically no reliable indication of what is happening to the machine he operates.

A year or two ago the B.E.A. compiled a record of the reported shaft faults in the past $4\frac{1}{2}$ years on a group of about 95 machines. In that group over a period of $4\frac{1}{2}$ years there had been 12 major shaft faults. Quite a number of those machines were not fitted with the type of equipment described, and there is little doubt that a number of the faults would have been prevented had it been available. To emphasize the cost of this type of fault, the outage of a 60 MW machine may amount to as much as £10 000 per week in additional fuel and other costs. Against that background, the cost of the equipment described in the papers does not seem very large.

The second main use to which this equipment can be put is in connection with the quick starting of machines. There are two main reasons for the desirability of quick starting. The first, of course, is to meet the load itself. In the morning the load on the supply system rises at a maximum rate of about 3 000 MW in half an hour. This is at a time when the total system load is between 10 000 and 13 000 MW, and the percentage is about 0·9% per minute. These figures, however, are the average for the whole country and the average for half an hour. There is no doubt that in certain periods of that half an hour and in certain parts of the country the rate of rise of load is not less than 1% per minute, and the machines clearly have to meet that rate of rise as a minimum.

The second objective in quick starting is, of course, to reduce the costs of operating plant under the relatively inefficient conditions of running-up, and of keeping an excessive amount of spare plant on the busbars. We have made an estimate of the approximate value of quick starting. It is hard to estimate these figures, because we do not know how much quicker we shall be able to start the machines; but the probable saving on the system of this country as a whole will be about £700 000 per annum if we can get a reasonable acceleration in the present rate of starting machines. The type of equipment described in the papers will assist us to that end.

The equipment described measures the physical movements principally of the rotor relative to the cylinder of the machine, but these, of course, are not the only factors affecting the safety of starting. There may be distortion of the cylinder itself by hogging or bending. Some work on that subject has been published in Belgium.* Also there seems to be no very clear knowledge of the stresses induced in large bodies of metal subjected to temperature differentials which may exist in starting. Do the authors consider it practicable to measure such stresses, and if so, how would they do it?

Comdr. J. H. Joughin: In naval ships there are two possible ways in which this equipment might be used. One is in prototype ships when we send the machinery to sea and obtain records from it, and the other, of course, is in the running of ships. At present, it is not so much the cost of this equipment as its bulk and maintenance which deter us from using it.

With regard to axial differential expansion, we should like to be able to make measurements in the prototype ship and then produce designs such that, no matter how badly the machinery were thereafter operated, that axial differential expansion could never be taken up. Eccentricity presents a different problem. Running speeds are doubled, so that sensitivity must be quadrupled, while at the same time the foundations are a great deal flimsier. I inspected a land set having 0·005 in eccentricity. The rotor was larger than the rotors we use, but when I stood on the massive foundation I thought that if it had been in a naval ship it would have shaken the engine-room to bits. I feel that we have not encountered more trouble than we have simply because our flimsy foundations tell us whether eccentricity is present.

So far we have not encountered temperatures above 850° F, and we have not had trouble from turbine eccentricity, although we have taken one set up from zero to full power in under 2 min. Of course, that is a very much smaller turbine than the authors have in mind. The homogeneity of the forging may have some effect, while our use of nozzle control may raise the temperature up "kindly" to the rotor as we increase the power.

In the last few years we have used temperature control. We do not let in steam at under 600° F, and whenever we are manoeuvring we try to keep the steam temperature below 750° F. It is not until conditions have become stabilized that we take the temperature to 850° F.

* GODFROID, J., and JAUMOTTE, A.: "Le controle du démarrage des turbines à vapeur," *Bulletin de l'Union des Exploitations Electriques en Belgique*, May, 1954.

It is in standby conditions that we encounter trouble; our l.p. rotors bend and have caused trouble owing to vibration. In a ship it may not be possible to control or shut down the load in the same way as in a power station. Usually a small amount of power will keep the ship under control, and if we can keep the machine running gently we can probably keep the ship going while we ease out this vibration; but it is partly because we cannot really control the machine that we feel we must have control of the temperature.

With regard to the interpretation of eccentricity readings in Section 5 of the paper by Messrs. Ashworth, Hall and Gray, it must be remembered that this is a convention which is laid down. I am not sure whether all these machines are running above their first critical speed or below it, but it hardly covers the case where they are running above the first critical speed. If the bend is in the gland at each end we may actually have only one-quarter of that displacement of the centre of gravity or centre of mass of the rotor.

Is it likely that the bulk of this equipment can be very drastically reduced? It would be of interest to use it in prototype new ships in order to obtain measurements of differential expansion in particular.

Mr. E. Hywel Jones: I will confine my remarks to the paper by Messrs. Ashworth, Hall and Gray.

I would make a plea for the use of the word "turbovisory" instead of "supervisory." "Turbovisory" is an elegant word which indicates very nearly what this new type of apparatus does. The term "supervisory" suggests administration and management and may well be dropped in this connection.

With regard to the second type of apparatus, there is a tendency for the operating staff to treat it with very great respect. They are always concerned about the indications, and consequently they run a machine up much more carefully than they used to do. Occasionally that may lead to delays, but with extended experience of the apparatus, occasions when needless delays are caused will become fewer.

In the South Wales area turbovisory equipment is installed at two stations, and we have never had a bent shaft at either station. Whilst this may be fortuitous, we also feel that the turbovisory equipment has assisted. If permanent damage to shafts and their sealing devices can be avoided, there is no doubt that the cost of the apparatus is completely justified.

On one occasion we had a blade failure, and the only indication was an increase in eccentricity, as shown on the instrument, of 0·005–0·011 in; this was treated seriously. Two or three attempts at running up were made and the eccentricity still persisted. Finally the i.p. casing was opened and the damage was discovered. The ordinary methods of feeling around the machine would never have disclosed this defect, and much more serious damage would have been caused.

We find that the apparatus is extremely reliable and maintenance is not troublesome. There may be a tendency to feel that electronic devices of this kind require constant attention, rather like the carbon-dioxide apparatus in a boiler house, but that has not been our experience. Once installed, the instrument continues to give its indication, and I know of only one case where for a short period the indications were unreliable.

It may be of interest to give some information about the maintenance costs. Over 9 500 running hours, the labour charges for routine maintenance averaged £6 5s. per month, and the cost of replacements over the whole period were £22 18s.; this covers two turbo-alternators.

With our present knowledge it is hard to interpret the readings. So many different factors can influence the running of a machine that I suppose we must continue for some time collecting experience and realizing slowly what the indications mean.

At present, the lighter end of a turbo-alternator is equipped with turbovisory equipment, on the principle that any vibration will appear at that end. This is rather like "the tail wagging the dog," and I wonder whether it would not be a good idea to equip one or two machines very fully with recording devices on all the shafts. With full equipment of this type it is possible that a better understanding would be obtained of what is occurring.

Mr. C. F. Smith: With the advent of the turbovisory equipment described in the paper by Messrs. Ashworth, Hall and Gray, many new and puzzling features of turbine behaviour have been found, and plant operators of many years' experience have been faced with problems of turbine behaviour which previously they had not known were present. Thus if the turbovisory gear is to be of benefit, operators must learn to interpret the printed intelligence instantly and know the remedies for each fluctuation, because if a quick start is being attempted, there is no time for pondering and research.

The turbovisory equipment described by the authors only records the diameter of displacement between the coils, the eccentricity and relative expansion. The operator has to deduce the causes of the eccentricity printed, which may pose any of the following problems: With a shaft bend, where is it bent? Is the rotor running concentrically in the bearing? Is the bend caused by uneven heating of the shaft by pinched-on gland sleeves? Is the shaft being "wagged" by the coupling? Is the shaft being subjected to oil whirl? Is the cylinder contracting?

It may not be appreciated that, of the preceding causes of shaft eccentricity, only one causes severe vibration with small values of eccentricity, i.e. the true bend, with the bend in the centre of the rotor mass. The others will cause tremors, but more alarm than damage will result if the fault is not allowed to persist. Here lies the value of the turbovisory equipment. If any of the phenomena occur on a machine not fitted with turbovisory equipment, the operator is ignorant of any occurrence or fault until the machine starts to vibrate, when it is usually too late to prevent any damage. Eccentricities up to 0·014 in can be obtained in certain circumstances with no more than the usual vibration. I should like to give some examples of which I have had experience.

The first is of a transient bend caused by uneven heating of the rotor by "pinched-on" gland sleeves. This turbine has its glands sealed with saturated steam. It had been noticed that, as the load increased on the set and the h.p.-gland steam was reduced or turned off, the eccentricity rose suddenly; so that it was normal station practice gradually to reduce the gland steam as the load increased in order to keep the eccentricity normal. It was decided to leave the gland steam on up to a load of 10 MW and then shut it off quickly. The eccentricity immediately rose from 0·0015 to 0·009 in as the sleeves warmed up, owing to the reasons stated by the authors, and after 4 min it returned to normal. It is important to note that no roughness in running was noticed throughout the whole period.

The second example concerns eccentricity due to coupling wobble. During a heat-consumption test at 60% on a 900 lb/in^2 900°F 3-cylinder turbo-alternator, the eccentricity started to rise from 0·0015 to 0·009 in over a period of two hours. The station staff consulted me about shutting down to investigate this problem, because they had received instructions to do so if the eccentricity reached 0·007 in. The set was running very well and no excessive vibration was felt. On my recommendation and reasoning the test, which had 20 min to run, was allowed to continue. As soon as the test was finished, the set was loaded to 45 MW, by which time the eccentricity had reached 0·014 in and the set was just beginning to "roughen." By quick operation of the hand-speeder gear the load was brought quickly down to 20 MW. This sudden reduction allowed the coupling spring to

centralize, the eccentricity was reduced at once to 0·0015in, and full load was restored at 5MW/min with an eccentricity of 0·0015in.

The limitations of the present type of turbovisory gear are very obvious. Fig. 21 shows the type of equipment which experience has proved to be necessary for fitting on future machines. This equipment is a great improvement on the previous ones, which only showed displacement at one fixed point, and gives the whole picture required by the turbine driver at a glance.

Prof. M. G. Say: In the paper by Messrs. Antrich, Gardiner and Hilton it is found that the magnetic qualities of the shaft disc are important, whereas in the paper by Messrs. Ashworth, Hall and Gray it is found that the shaft is quite satisfactory as it stands. What is the explanation of this?

The general measurement techniques in each case derive from standard telecommunication methods. Thus Fig. 6 of the paper by Messrs. Antrich, Gardiner and Hilton shows the discriminator employed in frequency-modulation reception, while Fig. 2 of that paper and Fig. 3 of the paper by Messrs. Ashworth, Hall and Gray show simple amplitude-modulation detection similar to that for the common domestic radio receiver. Both methods start from substantially the same signal (derived from a varying inductor) but show interesting differences of approach in the subsequent handling. One uses a permanent-magnet generator and barrier-layer rectifiers, following the technique of line telephony; while the other relies on thermionic valves. The organizations concerned are fortunate in having electronic departments which are able to assist in the solution of problems of this type—an indication of the increasing overlap of the light and heavy electrical-engineering fields.

Dr. R. J. Eldred: Turbine supervisory gear is not cheap and involves appreciable maintenance. It serves as a means of checking the mechanical condition of a machine during starting and running. The value of this increases with the size of the unit and the severity of the steam conditions.

However, there are a very large number of turbines in which the size and steam conditions are such as to render uneconomic the provision of supervisory equipment of the type dealt with in the two papers. Such small stations are usually designed with the idea that a turbine driver will be stationed close to the operating end of the machine. The steam conditions and size of the machine are such as to render remote, while the machine is on load, the possibility of trouble which could have been avoided had supervisory gear been installed. The only remaining aspect of supervisory equipment not discounted in these smaller stations is the assistance given during starting, and for this purpose, very much simpler and cheaper apparatus can serve quite well. For starting, the turbine driver requires to know:

(*a*) Differential expansion, which can be readily indicated by a mechanical indicator making contact with a collar on the shaft at the end remote from the thrust bearing.

(*b*) Cylinder expansion, which is readily indicated by a vernier scale attached to the sliding pedestal.

(*c*) Shaft eccentricity at low speeds, i.e. in order to ensure that the shaft is satisfactorily straight before raising speed. For this purpose a simple dial indicator or vibrometer can and has been used with satisfactory results.

(*d*) With medium-sized sets, where the normal temperature is 800–850°F, it is advisable to add a simple means of indicating the temperatures of the incoming steam and the casing metal at various points, e.g. steam chest and flange bolt. In order to obtain the trends of these temperatures it is sufficient to use a normal multiple-point temperature recorder with a fairly high chart speed.

With this comparatively simple instrumentation the turbine driver can start up his machine in the shortest time consistent with safety. The full supervisory gear cannot do more, but has the advantage that its indications are presented away from the machine and can be incorporated in the equipment of a central control room with, if desired, means for the remote starting of the machine by the unit control engineer.

This is obviously the next development to be associated with turbine supervisory gear, and we should regard the type of installation at present in service as but a stage in the development towards centralized and, possibly, semi-automatic control. For such a purpose, it is absolutely essential that normal deterioration of the components should not falsify the indications and that breakdowns should be immediately obvious. It is questionable whether that stage has yet been reached.

Mr. D. Clark: The B.E.A. hope very shortly to order a 200MW turbo-alternator set; I expect the cost will be about £2 million, and the turbine alone will possibly account for, say, £750 000. I think that these figures indicate the scope available for equipment of this kind to pay its way, if it can help to ensure the safety and the high availability of that type of unit.

There is no point in spending a great deal of money on equipment unless we are also prepared to pay for operators who can use it to the best advantage. Technique is changing very rapidly. Mr. Shakeshaft mentioned the number of sets of 100MW capacity and above which are already on order. The first will not come into service for over a year, but already we are on the threshold of ordering a 200MW unit, so that operators generally will be faced with some rather rapid changes, i.e. rapid by comparison with what has taken place in the last decade. I think that by conventional present-day standards the salaries and wages of all the staff concerned with the operation of this 200MW unit costing £2 million will probably total about £10 000 per annum. I do not suggest that more staff should be engaged, but in view of the advances being made in technique, is there not a case for "paying more for more brain"?

Mr. Peterson mentioned an early-morning rate of rise of load of 3 000MW in half an hour, or 100MW/min, and stated that that was probably about 1% of the capacity of the plant synchronized on the busbars at the same time. Of that capacity on the busbars, however, quite a large proportion at any one time will be fully loaded. Therefore, on the plant available to take an increase of load, the percentage rate of rise of output must be substantially larger than 1%.

Mr. W. Lloyd Williams: Supervisory gear has proved itself as an indicator of imminent trouble but has failed as yet to indicate the cause of the trouble. It is in the process of building up its case law. I believe that research with the use of the oscillograph tracing the locus of the shaft centre will help to make the causes of these troubles more quickly evident.

With reference to the station with which I am associated and which uses such gear, the greatest difficulty encountered is that of interpreting the indications, and the manufacturers also seem in doubt about this. Although we are uncertain of the meaning of these indications, nevertheless they afford a timely warning of coming events, and usually before they are perceptible to touch or hearing. We are thus able to put the brake on operations before conditions get out of control.

Turbine operation is now guided by this equipment, particularly during running-up and load changing. Although we have had turbine-vibration troubles, turbovisory gear has been helpful in preventing real shaft troubles.

The detector units in this installation are fitted at the free end of the lightest of three rigidly connected shafts, and it is apparent that indications do not necessarily reflect h.p. shaft troubles.

The following factors are reflected on eccentricity indication:

Variation of hydrogen-seal oil pressure.
Variation of condenser back pressure.
Variation of oil temperature generally.
Isolation of half a condenser for condenser cleaning.
Binding of a bled steam pipe on the turbine foundation block.

There was also one case of malalignment between the h.p. and the l.p. spindle, which was evidenced by an uneven gap between the couplings and which, when the set was fully loaded, produced an eccentricity on the l.p. end of the h.p. spindle of some 0·007 in. This was accompanied by rough running. The set could be made to run smoothly, and the eccentricity returned to normal, by any of the following adjustments:

(*a*) Reducing the load from 60 to 54 MW.
(*b*) Raising the oil temperature to the bearings from 100°C to 122°C (120°C was no use).
(*c*) Raising the condenser back-pressure from 1 to 1·5 lb/in².

The most useful indications, and the quickest guide to possible trouble, are those of horizontal eccentricity. Vertical eccentricity does not give an early indication but acts as a confirmation of horizontal eccentricity.

The axial-displacement indicator is a duplication of the shaft poker gauge, but it is much better displayed and much more sensitive. Moreover, it is a record, and records show trends which are extremely important in matters of this kind. It is of particular use when running up after short shut-down periods, when there is a distinct danger in admitting steam to the turbine at a temperature lower than that at which the cylinder may be. The relative movement is then in the direction in which there is the smallest clearance.

In conclusion, the equipment fitted has been reliable and has given accurate indications. Turbine operation is now governed by a set of indications, the causes of which are not fully understood, but we rely upon them so much that we should feel almost blind if forced to do without them. The gear should be regarded as a necessity on all large h.p. turbines.

Mr. H. S. Holden: I wonder whether the manufacturers themselves really believe in the information this type of equipment gives. There seems little attempt to eliminate the elementary matters which affect the running of the machines, and I was interested in Mr. Shakeshaft's comments on the lubrication of turbine sliding surfaces and other similar features now being tackled in America. It is very difficult to convince manufacturers that this is really necessary, although a great deal of proof is available, and I doubt whether any set in this country installed over five years ago is now able to expand as freely as it should. Other elementary lapses are evident, e.g. the provision made for cooling-gland sealing steam. I wonder what happens when this is reintroduced to glands after being shut off for a time. The accumulated water perhaps carries forward unless permanent draining is made available.

The evidence we have available would indicate that the i.p.-cylinder and rotor supervisory equipment give the majority of abnormal indications, and very little is indicated on the h.p. cylinder and rotor which gives cause for concern.

Mr. G. McK. S. Sichel: It must be remembered that the development of supervisory gear is of comparatively recent origin. It has been proved that it is a very useful tool, and we are now able to understand what happens when vibration is experienced. In the early days we had our two hands, and that was our only supervisory gear; we ran the plant up and if it "ran rough" we had to "humour it." With this apparatus we know what is going on but we do not know the whole story, and as many speakers have pointed out, one of the main difficulties is to know how to interpret the results which are obtained. If we can reproduce a set of results we can build up a theory to explain them, but one of the difficulties is to obtain a second set of readings which are identical to the first.

I should like to mention one experience in which I was able to do this. In running up a three-cylinder turbine, at the instant we put gland steam on, vibration immediately developed. In order to find out which gland was responsible we turned off the steam one gland at a time, and finally came to the i.p. inlet gland. The eccentricity increased sharply to 5 mils when steam was applied; when the steam was turned off this gland, the eccentricity returned to zero while we were looking at the instrument. Steam was reapplied to the gland and the eccentricity immediately increased to 5 mils. These readings could be reproduced as often as desired. This could be described as a "controlled condition," and it was possible to construct a theory to explain it. At the same time I cannot understand why the application of gland steam to a shaft which was running at about half speed (1 500 r.p.m.) produced a condition of eccentricity. I would have expected that, if one wanted to warm up a shaft uniformly, the best way would be to apply the steam or heat while the shaft was rotating, but in this case it had just the opposite effect.

I should like to give another example, of recent origin, which cannot be explained. A new boiler was being brought on line, and owing to some unforeseen factor, an h.p. turbine which was running on load got a "fairly big dose of water." The average operating engineer would probably imagine that it would immediately contract the shaft, but the recorder instrument showed no movement at all. The station engineer expressed doubts about the accuracy of the instrument, because he thought that there was bound to have been shaft contraction. An experiment was therefore made by actually moving the shaft axially and checking the measured movement of the shaft against the movement recorded on the instrument; the readings were practically identical. We must deduce from this, therefore, that if water enters a hot machine in that way it does not necessarily follow that the shaft contracts.

[The authors' replies to the above discussion will be found on page 154.]

NORTH STAFFORDSHIRE SUB-CENTRE, AT STAFFORD, 22ND NOVEMBER, 1954*

Mr. L. A. E. Fosbrooke: It is essential that supervisory equipment should be installed on i.p. as well as h.p. turbines, particularly when fine clearances between the blades are involved.

On a 60 MW-unit plant in the Midlands Division of the B.E.A. the h.p. turbine failed when running up, although the supervisory gear associated with that turbine showed that conditions within it were satisfactory.

The impression gained at the time was that a vibration developed in the i.p. turbine, which was transmitted to the h.p. turbine rotor when it was accelerating through its critical speed. As a result of this incident, supervisory gear was installed on the i.p. turbine. Through this equipment, during a subsequent run-up under identical conditions to those on the occasion when the failure occurred, it was found that the clearances between the running and fixed blades were rapidly decreasing. In spite of the precautionary measure taken in adjusting the thrust-block position, it was obvious that damage would be sustained. The turbine had to be shut down immediately, and modifications were made to the thrust adjustment gear to accommodate this abnormal condition. It is impossible to run up this particular machine without supervisory equipment, owing to the extreme flexibility of the h.p. turbine rotor, the mass ratio of which, compared with its casing, is about 1 : 7. As the critical speed of this rotor is 2 000 r.p.m. it was first necessary to bring the machine up to a speed of 1 700 r.p.m., and having ascertained from the supervisory equipment that this rotor was expanding relatively at a greater rate than its casing, it was then

* This refers to the paper by Messrs. Ashworth, Hall and Gray only.

necessary to accelerate the machine through the critical speed to the running speed of 3 000r.p.m. in approximately 15sec, in order to prevent the h.p. rotor from whipping.

A quick-checking arrangement of the supervisory equipment should always be provided, the simplest form of which would be for a turbine driver to throw over a switch which would bring all the indications to predetermined positions, thereby showing that readings given by the pick-up coils were correct.

With reference to the trouble experienced with a high-pressure gland sleeve causing an increase in eccentricity when excessive changes of steam temperature occurred thereon, it is possible for the sleeve to expand sufficiently rapidly, thereby causing it to lose its uniform contact with the shaft, which would result in non-uniform flow of heat into the shaft at the remaining points of contact. This would cause unequal heating of the shaft within the gland, and consequent distortion with attendant eccentricity.

[The authors' reply to the above discussion will be found on page 154.]

NORTH-WESTERN SUPPLY GROUP, AT MANCHESTER, 30TH NOVEMBER, 1954*

Mr. J. W. Steeley: One of the prototype models was installed in my present station on a 25MW 3 000r.p.m. impulse machine some 8 or 9 years ago after serious blade failure. The modifications carried out by the manufacturers to the machine were so successful, however, that no further trouble was experienced, and the turbovisory equipment was never referred to and became merely an ornament in the turbine house.

It was in that frame of mind that the station engineers approached the use of this equipment as an aid to operation when commissioning the 60MW unit mentioned in the early part of the paper. Initially great concern was shown during run-ups if the eccentricity chart recorded a figure in excess of 2 mils; but after long and laborious initial troubles, this machine was at times put on load with eccentricities of up to 8 mils with little or no vibration. The machine is running at present with an eccentricity varying between 2·5 and 4 mils, depending upon the output. Some of this may be due to "shaft roll." What investigations are being carried out on this phenomenon, and will it be possible to differentiate between it and true eccentricity? We would all agree that, once the operator understands and can interpret the readings given by the turbovisory equipment, he can have complete faith in the picture it gives and act accordingly. In my opinion the main thing is not the actual eccentricity reading, although this is naturally important, but its rate of increase, since this dictates the operator's reactions. I am glad that the authors acknowledge the operating engineers' reluctance to run up to full speed and possibly load a machine with a contracting cylinder even when the differential expansion is within tolerable limits, but with the normal aids provided and no explanation at present available, it is as well to follow the golden rule. The use of flange steam has been found to be of value in this respect in hastening the process with a hot machine.

Mention is made in the paper of misalignment of the h.p. pedestal keys on one machine, which causes restrained movement of the cylinder; this was shown by irregularities in the differential record.

It is not so widely known that, although the keys and key-ways were examined and alignment improved so that restraint either way was negligible, the movement of the h.p. pedestal and therefore the cylinder was crab-wise—not much, but sufficient to be recorded on clock gauges.

We have counteracted this tendency by splitting the flange-heating steam supply so that the quantities to the left-hand and right-hand flanges are separately controllable. Pressure gauges have been fitted in these lines, and normal operating pressures vary between 50 and 100lb/in^2. This arrangement has been found of value particularly on running up a cold turbine when the crab-wise movement is more pronounced. What are the authors' views on this arrangement, and has any further thought been given to the practicability of greasing the centre key?

These remarks apply particularly to Fig. 7 on which the authors remark that unnecessary caution appeared to have been taken during the initial period of running up. With rapidly increasing differential expansion, we were endeavouring to obtain positive cylinder movement in the right direction with liberal use of flange steam.

The description of the run-up shown in Fig. 11 is interesting, but I feel that, under normal operating conditions, the set would have been synchronized at 1040 hours. Do the authors agree, and can they state whether any undue vibration could be felt at the trip points?

I was interested in the experience gained on the gas turbine with turbovisory equipment. Do the authors consider that this is now a satisfactory state of affairs for a machine intended for peak-load operation, or are steps being taken to reduce these times still further?

Mr. W. Davies: The bending during running-up on a contracting machine is associated with the flexible couplings used to join the rotors. This type of coupling has been in successful use for many years, but higher steam conditions and ratings have meant that the power developed in a rotor of given size is, at present, twice or three times that developed in a comparable rotor constructed, say, 20 years ago, and necessitates a larger coupling. Improvements in design and manufacture have produced rotors suitable for modern requirements, but improvements in design and manufacture of flexible couplings have not proved adequate.

If, under contracting conditions, the coupling halves are not free to move and if the torque is taken at one point in the coupling, the rotor becomes a strut subject to an eccentric load, and a bend of appreciable magnitude may be produced.

When a rise in eccentricity reading is observed there are three courses of action, depending on the circumstances, for the operator to follow:

(*a*) If the rotor runs through a critical speed and the speed is in this region, the rise will be normal, and the speed should be increased quickly. The degree of roughness through the critical speed range depends on rotor balance, and the value of the turbovisory gear in this instance is that it enables the operator to verify that the rotor is straight—and in good balance—before entering the critical speed range.

(*b*) If the steam is shut off suddenly the eccentricity may rise as illustrated at 1054 hours in Fig. 5. It is better to maintain constant speed by controlling the steam flow. If the eccentricity does not decrease, speed should be reduced and the shaft straightened at a low speed. In general, with a bend that persists, time is gained by this process.

(*c*) If the bend arises from rigidity in the coupling the thrust collar will be pushed away from the main pads, and the hydraulic type of axial position indicator fitted to the machines described will provide an additional aid to diagnosis. A reduction in the indicator pressure suggests that coupling lock is causing the bend, and the operator should reduce the steam flow suddenly to release the torque on the coupling and allow a readjustment of the springs.

This suggests an alternative explanation to the occurrence shown in Fig. 8. Prior to 1130 hours, the differential-expansion indication shows that the rotor may be in a state of compression. Immediately after the drop in speed the rotor begins to contract relatively and is in a state of tension. In this condition the shaft straightens, as indicated by the falling eccentricity reading, even when the speed is being increased.

* This refers to the paper by Messrs. Ashworth, Hall and Gray only.

After 1230 hours the rotor begins to bend—although slightly—as the differential expansion again indicates the possibility that the rotor may be under compression.

Mr. W. S. Ross: I have made many quick-starting trials with 60 MW and 3 000 r.p.m. 900°F machines of other manufacture. They were provided with the authors' equipment, and I can testify to its worth and reliability. For the first time, mechanical behaviour at speed and on load could be studied as readily as thermal performance.

The skilled drivers appreciated the supervisory apparatus. However, there were not enough of them to operate all the large high-temperature installations coming into service, and this apparatus greatly helped the less experienced ones, while the records could assist those who had to train them.

With regard to the 1 500 rp.m. unit the authors suggested that vibration might occur if the machine was run up while contracting, but when discussing the 3 000 r.p.m. unit, they suggested that vibration was caused by the application of hot steam to a cool h.p. rotor. During the shut-downs of moderate length, I have found that most of the cooling (and hence most of the contraction) was confined to the casing and rotor at the h.p. inlet. The contracting cylinder was thus an indication that the inlet end of the h.p. rotor was at reduced temperature, and that application of hot steam to it might produce undesirable effects. Therefore the two suggestions seemed to be consistent.

The machines I have tested had no separate shaft liners, as described by the authors. They could be started and loaded very rapidly without vibration, when contracting and even when cold. Vibration equipment similar to that described in Section 8.2 was fitted during the tests, and I supply comparative results in Table A. The eccentricity readings normally followed a definite pattern, any departure from which would have been a danger signal. However, could the authors comment on why the eccentricity amplitudes were so much greater than the vibration amplitudes in this particular case?

Table A

Condition of machine at starting	Hot and contracting		Shut down for 8–12 hours		Completely cooled down	
Amplitudes	Eccentricity × 2	Vibration	Eccentricity × 2	Vibration	Eccentricity × 2	Vibration
	in	in	in	in	in	in
On speed	0·002	0·0005	0·007	0·0007	0·0015	0·0004
On load (initially)	0·010	0·0008	0·010	0·0008	0·004	0·0006
Minimum values reached while building up load	0·007	0·0007	0·007	0·0005	0·003	0·0005
Full load	0·010	0·0008	0·010	0·0008	0·004	0·0006

Once full load had been reached, a steady reduction of these figures was always observed.

In Section 1 there is a reference to "additional information." If abnormal supervisory readings are obtained all relevant supplementary information should be entered in the station log, otherwise subsequent diagnosis is hampered.

In Section 7 it was demonstrated how information provided by supervisory equipment could, with advantage, be followed up by more detailed tests. During loading tests I carried out, the equipment revealed hitherto unsuspected reductions in axial clearances and made possible operation methods which eliminated this difficulty.

Mr. H. C. Young: Prior to the use of turbovisory equipment, the procedure for starting large steam turbines using elevated steam conditions, and the time taken to reach synchronous speed, depended largely upon the judgment of individual drivers, and thus inconsistency could be expected. Some drivers, mostly those of the old school, tended to regard the installation of mechanical eccentricity indicators or turbovisory equipment as a reflection on their skill, sometimes becoming bewildered where an increase of eccentricity with speed became apparent without noticeable reflection in the running balance, as judged by their "feel" of the bearing housings.

I fully agree with the authors' views that rotor-shaft bending mainly results from unstable thermal conditions; nevertheless the equipment also records any displacement a rotor journal may make in its bearing oil clearance, especially at low speeds before the establishment of a stable lubricating oil flow at normal working temperatures has been established. The eccentricity as recorded may therefore be due to shaft bending, journal excursion round its bearing, or a combination of both.

On observing the start of a large high-pressure steam turbine, first with the lubricating oil preheated to the normal inlet working temperature and then with cold oil—in each case with a cool turbine cylinder such as would obtain after a protracted shut-down—a substantial reduction of eccentricity was apparent in the case of the preheated oil at the lower speeds where the maximum eccentricity occurred, as shown in the various diagrams in the paper.

Experience is necessary in interpreting turbovisory records, and cases are known where, at synchronous speed, eccentricities in excess of those given by the authors have been observed without deterioration of the running balance as noted by use of a portable vibrograph, which gave results within the accepted standard. Therefore the inclusion of the vibration recorder in the equipment appears essential, while the recording of the inlet lubricating-oil temperature might be useful in facilitating the correct interpretation of the turbovisory readings.

Mr. D. Ruby: Since the authors specifically mentioned the use of supervisory gear as an aid to the rapid starting and loading of turbo-generators, and it has been established that varying temperatures between turbine parts can prevent this, have the authors any information regarding measures of temperature control in order to avoid the differential expansion between the rotating and static parts of the turbine?

Mr. J. Tozer: Would the authors be prepared to operate a turbo-alternator remotely from a control room situated probably between the machine and the boilers? It would be interesting to know what alarms they would recommend.

The paper describes equipment for impulse turbines, but have the authors had any experience with equipment for reaction turbines?

I suggest that the complete turbovisory equipment shown in Fig. 21 could be improved by the addition of information regarding pressure and temperature at the boiler stop-valve.

In Section 3(*a*) mention is made of erratic readings due to voltage disturbance. Can the authors state what voltage tolerances can be allowed?

Mr. J. R. Appleton: With regard to Fig. 8, the start is made with a cold turbine where full speed has been attained in approximately one hour and with relatively cold steam. As soon as load was applied, heating would be rapid, and eccentricity is a danger under those conditions. If full steam temperature had been available from the beginning, or a longer time taken, I think the eccentricity would have been less. It is not possible to prevent an increase in temperature when load is applied, but the rate of rise should be kept to a minimum by careful operation of the plant in order to ensure that the steam pipe is thoroughly heated before the rush of load steam. I much prefer a speed curve similar to that shown in Fig. 9.

On one occasion at Carrington, turbovisory equipment has proved of value when a steady increase in eccentricity over several days was observed. When the turbine was examined, the alignment was found to be faulty, and fretting of the bearing housing had already commended. This eccentricity should not be confused with bending of the shaft.

Each turbine has its own characteristic eccentricity, both during starting and when on load, and it is necessary for early records to be available for reference. The record of the turbine slowing down after a long period on load is of great value.

We have fitted a mercury-in-steel recording thermometer into the steam inlet belt through the lower flange of the h.p. cylinder. Approximately half of the mercury bulb is in the steam and half in the metal, and the recorder is mounted on the hand rails round the turbine block so that vibration is also recorded. The thermometer gives a pessimistic reading, since the large mass of metal constituting the flanges cannot be heated as rapidly as the rotor. This feature is desirable during the starting of the turbine, since it means that if this mass of metal has attained approximately stable temperature conditions, the rotor must have done so. On the few occasions when starting from cold, and when an attempt has been made to increase the speed above 1 000 r.p.m. before this stable temperature (approximately 500° F) has been reached, increased eccentricity has resulted and, on one occasion, severe vibration. I would not suggest that the turbines could not be run up to speed before the temperature of 500° F has been reached, but I feel that difficulty with eccentricity is more likely to occur, and the time lost in correcting this is usually more than the time required to obtain this temperature. This is important when load requirements have to be met. If the turbine is still hot, difficulty is not experienced, and the quicker the turbine is speeded up and put on load the less is the eccentricity.

THE AUTHORS' REPLIES TO THE ABOVE DISCUSSIONS

Messrs. D. Antrich, H. W. B. Gardiner, and **R. K. Hilton** (*in reply*): We fully agree with Mr. Shakeshaft concerning the part that supervisory equipment plays in the operation of large power units. It is easily possible to extend the range of such gear to measure other variables such as vibration, temperatures, etc., so far as it is advisable in practice, but above all it is particularly desirable that all readings may be co-ordinated in time with the speed and load under which the set is running.

Mr. Hutchinson stresses the importance of such equipment being as reliable as possible, otherwise maintenance may be appreciable. Such reliability is also essential from the psychological aspect, since the indications given by the equipment will not be given their true significance unless there is an instinctive feeling that they may be relied upon for accuracy.

Mr. Peterson asks whether it would be practical to measure cylinder distortion; there would be no difficulty in this, if it were considered desirable. With regard to the measurement of stresses, this could be done, but it might be better to do it as a separate experimental set-up, rather than complicate supervisory equipment with additional indications of a highly technical nature.

In reply to Comdr. Joughin, we see no reason why, with a certain amount of development, the size of the equipment could not be reduced for application to marine turbines. We agree that the application of a trial equipment on a prototype installation would be of value; it would also soon permit an assessment of its usefulness, and enable a decision to be made as to whether it would be worth fitting to further installations of the same type.

With regard to Prof. Say's comment on the relative importance of the effect of the magnetic qualities of the shaft, we suggest that the reason may lie in the choice of frequency and air-gaps; the overall characteristic of the equipment depends on the combination of these factors.

We cannot agree with Dr. Eldred that supervisory gear involves considerable maintenance. Problems of starting and running a turbine increase greatly with size; it is probably true that small sets running on moderate steam conditions require little or no additional equipment, but on large sets the cost of the supervisory gear may be considered a small insurance premium to pay for reliability, and if it avoids one major shut-down it may more than compensate for its cost. We would also like to stress the great value of chart records. It is surprising how much information, which would be otherwise unknown, can be deduced from an analysis of chart records, and to omit them is to miss one of the main advantages of installing such equipment.

We agree with Mr. Lloyd Williams that supervisory gear shows the effects but does not give the causes. Only with careful analysis of records, aided by more experience, can one deduce the cause of any particular trouble, and as time goes on, more knowledge will be gained.

Messrs. J. L. Ashworth, J. S. Hall and **A. H. Gray** (*in reply*): Mr. Shakeshaft's remarks constitute an acute and comprehensive summary of the problems relating to smooth running and quick starting on which turbine designers are engaged at present. We foresee that it may take another decade before the problems revealed by the use of turbovisory gear are satisfactorily solved. We believe that turbovisory gear must be kept within bounds, and that every item must be strictly justified by an important and properly understood purpose.

In reply to Mr. Hutchinson, it must be admitted that the records given in Section 4.1 are largely historical, and indicate the kind of operational difficulty and uncertainty that brought turbovisory gear into being. Temperature differentials were not recorded at that time. If the theory advanced to explain the bend of Fig. 5 is correct, there do not appear to be any grounds for thinking that increased barring speed would have avoided the bend. We have no experience of supervisory investigations other than on impulse turbines. We are also strongly in favour of close co-ordination of boiler and turbine characteristics.

Mr. Peterson contributes important and impressive figures, and we agree that the causes and effects of cylinder distortion are only very vaguely understood. We do not know of a satisfactory method of measuring stress in, say, a hot cylinder end, but it would appear to come in the category of problems whose solution only waits the application of sufficient effort.

In reply to Comdr. Joughin, marine turbines have the advantages that their speed varies with the load, and that they are always under load when turning. Thus they are heated by relatively large quantities of steam while still turning at low speeds. This is probably the factor which is "kind" to marine turbine rotors, but temperature control is, of course, the most satisfactory

method of preventing bending. A stationary rotor is almost certain to bend owing to the temperature gradient in the cylinder. Comdr. Joughin will also be pleased to learn that the new design of the turbovisory equipment now available is considerably smaller than the gear demonstrated.

Mr. Hywel Jones's contribution is a fair assessment of the present situation with regard to the value of turbovisory instruments. We also agree that there is much to be learnt about the mechanical, rather than thermal, effects associated with the "tail wagging the dog."

We are keenly aware of the problems detailed by Mr. Smith, and greatly value the experience and observations embodied in his contribution.

In reply to Prof. Say, we agree that these measurements arise from a common source. The latest design preserves the same fundamental principles but seeks to reduce maintenance still further by omitting expendable items. With regard to the magnetic properties of the rotor shaft, we can only reiterate that experience substantiates the fact that the rotor shaft itself is quite suitable for this measurement.

We agree with Dr. Eldred's summary of the essential information required at starting. However, if we assume that there is a case for instrumentation at all, his summary only applies when everything goes according to plan, and only if he has already established a foolproof starting technique, which ensures for instance that only dry steam is admitted to the turbine and glands, or correct oil temperatures. It is on the possibility of the technique not being foolproof that the case for electrical eccentricity gear rests. If eccentricity gear is fitted, it is simple to add differential expansion gear.

In his remarks on the human element, Mr. Clark has raised a problem of concern to all who are responsible for the operation of large modern generating units, and in particular the very large units to be commissioned in the near future. In the last decade there has been a remarkable advance in the size and complexity of generating plant, which has been matched by an equal advance in instrumentation and control techniques. This is well illustrated in the United States, where, in many modern plants, control of operation has been centralized at one point, which results in a reduction of the number of operators. The system requires increased technical ability and places heavier responsibility on each individual operative. Discussion of the reward of labour is outside the scope of the paper, but we agree that there must be a high level of technical ability on the part of operators of the very large generating units to be installed in the near future.

We agree with Mr. Lloyd Williams that there is much to be learnt about the behaviour of journals in bearings, and much of the obscurity about the interpretation of turbovisory readings is probably due to ignorance on this matter.

Mr. Holden raises a number of detail points. The case against wet lubrication of sliding surfaces is based on the belief that the lubricant will soon collect foreign matter and form ridges by abrasion, or will carbonize and become useless, and block up its own channels. Dry graphite, or more recently molybdenum sulphite, has been preferred and appears to work well on suitable surfaces. However, the present need for reliable rapid starting may well make it worth while to consider means of overcoming the disadvantages of wet lubrication. We share Mr. Holden's apprehension of the effect of water entering with the gland steam.

Mr. Sichel contributes further experiences, and since his background dates from long before the initiation of turbovisory gear, his explanations are particularly valuable. We would suggest that his rotor which was subjected to a "fairly big dose of water" actually threw enough of it off on to the interior of the cylinder to avoid unequal cooling. Nevertheless the practice of allowing water to enter a hot turbine is strongly to be deprecated.

Mr. Fosbrooke refers to an experience in which the vibration of an i.p. rotor caused severe disturbance of the h.p. rotor when passing through its critical speed, and draws attention to a hazard which might not otherwise be anticipated.

We appreciate the part Mr. Steeley has played, and is still playing, in getting acquainted with turbovisory gear. There is undoubtedly a phenomenon of shaft roll, or whirl, and as he implies, it must be understood before turbovisory-gear readings can be properly interpreted. With regard to the control of the crab-wise progress of the h.p. pedestal by discriminate use of flange heating steam, comment must depend very largely on the amount of the irregularity. If there is a definite connection between "crabbing" and vibration, and flange steam used as described prevents the vibration normally present during heating, its use must be preventing distortion and would appear to be wholly advantageous. We do not know the mechanism whereby a crabbing pedestal produces rotor vibration. In connection with Fig. 11, we agree that normally the set would have been synchronized at 1040 hours, or possibly 0940 hours, but the start was prolonged in order to make experiments which it was hoped would throw light on the problem of interpretation.

Mr. Davies argues that the bending of shafts during cylinder contraction is due to coupling lock. If we do not consider this to be proven, it is only further evidence of the complexity of the problem of interpretation.

In reply to Mr. Ross, the inconsistency between eccentricity and vibration is, of course, the puzzle of turbovisory-gear interpretation. It has been shown that rotors often develop motion in which they rotate about an axis which is oblique to their geometric axis, both axes passing approximately through the centre of mass. The motion shows up as a large eccentricity, but vibration is not of a serious nature. In order to illustrate this motion we demonstrated a model rotor shaft, and showed that two sets of turbovisory magnets, one at each end of the shaft, could discriminate between the motion in question and a true bend.

Mr. Young refers to the curious fact that very large eccentricities are sometimes encountered at low speed, and suggests that their magnitude is influenced by the vicinity of the lubricating oil. We feel that ultimately it will be difficult to justify the fitting of vibrometer equipment as well as the much more precise and direct-reading eccentricity indicator.

In reply to Mr. Ruby, the question of temperature control is outside the scope of the paper. Much literature is already available on the subject.

In reply to Mr. Tozer, we would be prepared to operate from a remote control room. Details of procedure and alarm arrangements would take more space than can be allotted in this reply.

We would like to record our appreciation of the assistance we have received from Mr. Appleton in experiments associated with the interpretation of turbovisory readings. His contribution indicates his great interest in the subject, and in particular, his observations on the relations between temperature levels and speed during the starting sequence are very useful.

DISCUSSION ON "ELECTRICITY IN MEDICINE"*

Mr. J. C. Shaw (*communicated*): The increasing use of instrumentation in routine medical work calls for a much more widespread collaboration between clinicians and technical experts than is at present the case. The paper is therefore of immense value in bringing notice of this important field to professional engineers. Unfortunately the greater need is the converse problem of making the medical profession more "instrumentation minded," particularly in respect of the limitations of the instruments and instrument-patient system. The education of medical men about some of the technical features of the apparatus is a job which their technical colleagues should tackle at every opportunity. The manufacturers' advertising leaflet is often the only source of information which the clinician seeks when buying equipment, and this source is not always the best.

The author refers to instruments used for electric-shock therapy. A wide variety of shock-therapy instruments are now available on the market, and some of these are designed to eliminate the necessity for the therapist to understand anything of the electrical properties of the patient-instrument system under his control. One such instrument supplies mains alternating current via a step-down isolating transformer. The medical user knows the "voltage" is about 150 volts but seldom understands that this figure refers to the r.m.s. value. I have found many doctors astonished on being told that the peak voltage is of the order of 210 volts and that the voltage change may be twice this amount within 10millisec. There is an unfortunate ignorance on these simple points.

Again, one of the variables which has only recently been studied is the question of the minimum electrical-energy requirements to produce a convulsion in the patient, it being fairly well agreed that it is the physiological convulsion and not the electricity which is of therapeutic value. It has been shown that the classical procedure using 50c/s or 60c/s alternating current supplies more electrical energy than is necessary. There have been a great variety of electrical waveforms used in this treatment, and the method known as "brief-stimulus" therapy, which is now widely used in the United States, uses square-topped pulses of 1 millisec duration and frequency 120 or more per second. There is ample opportunity for further development of electric-shock-therapy instruments based on a sound knowledge of electrical theory and regard for the patient-instrument system.

Electric-shock therapy involves the use of a simple instrument by a large number of clinicians. Electro-encephalography, another field which the author discusses, involves a more limited number of instruments, but of a much more complex type. Here again, the limitations of the apparatus are not always appreciated by the medical personnel who use it. In this field also, expensive subsidiary apparatus is often bought with little understanding of its limitations and usefulness.

I should like to endorse the author's comments on the need for the proper servicing of equipment in a hospital. The availability of suitable technical advice would also prevent the misuse of apparatus.

Electrophysiology is now an important field of science combining relevant features of electrical science and physiology. While advances in physiology have often depended on technical improvements in instrumentation, electrophysiology has often had something to give electrical science in return. The voltaic pile was to some extent the outcome of Volta's arguments with Galvani as to the importance of contact potentials between metals over "animal electricity." Perhaps less well known is the fact that Thévenin's theorem is a particular case of a more general theorem developed by Helmholtz, when studying the analysis of current flow in volume conductors, a study which was the result of his interest in nervous conduction.

Mr. S. N. Pocock (*in reply*): The remarks of Mr. Shaw draw our attention to the poor standard of accuracy displayed in descriptive literature provided by many manufacturers of instruments both for therapy and diagnosis. This arises because the commercial success of a therapeutic instrument in particular depends upon the claims made in the clinician's own language. Indeed, any unit marketed with a specification written by an engineer would be doomed to failure. If the output impedance of an electronic stimulator (of considerable importance in diagnosis) was quoted other than by the words "low" or "very low" it is doubtful whether it would mean anything to the majority of users. Even safety precautions are not understood: I was once asked by a doctor in a large hospital why the instruction booklet for a shock-therapy unit stated that the metal case must be earthed as he found that it worked just as well when not earthed, quite unlike his radio receiver which appeared to require this connection. At the moment, however, a clinician who has a real understanding of the effect of the electrical characteristics of instruments often has considerable difficulty in obtaining true comparative performance data from manufacturers before purchase, because the sales departments are quite uninformed on these matters.

I am aware of the wide popularity of the "brief stimulus" method of shock therapy in the United States, but popularity in itself is no proof of superiority in this field. No convincing comparative work on a truly scientific basis has yet appeared to induce users in this country to change over from their simple 50c/s apparatus to rather complex and expensive equipment.

Both these subjects point to the necessity for an official body to investigate claims for treatment and diagnosis by electrical methods and to advise upon specifications for instruments and to give independent test reports on commercial instruments. This would do much to protect manufacturer, designer, user and patients from the difficulties and dangers of the present situation. It is a discouraging thought, but not an exaggeration, to say that the best efforts of a designer may never appear as a commercial instrument because its advantages pass unnoticed while low-cost units of poor construction and design, and even of low safety factor, enjoy popularity. In the particular case of electronic stimulators, cheap design and construction results in poor waveform, very poor stability of pulse duration and frequency (errors often being several hundred per cent), and variable output resistance conforming neither to the constant-voltage case nor to the constant-current case. The user never has an oscillograph available and continues with absolute faith in the instrument until complete failure occurs. When exported to tropical climates the performance of some instruments is in many instances truly appalling. The obstacle to sound engineering design represented by the unusually competitive market can be removed only by the certification of quality and performance and improved technical education of all those engaged in the use of electrical methods in medicine.

* Pocock, S. N.: Paper No. 1755 U, December, 1954 (see **101**, Part II, p. 629).

Abstract No. 1849
Mar. 1955

MERSEY AND NORTH WALES CENTRE: CHAIRMAN'S ADDRESS

By P. R. DUNN, B.Sc., Member.

"CABLES—SOME POST-WAR TRENDS"

(ABSTRACT *of Address delivered at* LIVERPOOL, 11*th October*, 1954.)

The uninitiated user, who generally takes cables very much for granted, may sometimes wonder what the cablemaker has to show for his laboratories and for the money he spends on them.

The times demand, and have seen, active technical advances. The use of electricity grows exponentially; transmission voltages continually rise; telecommunication frequencies have increased a thousandfold in the last decade; and new cable materials and techniques have been developed and exploited to meet these conditions. It may be of interest to survey what the cablemaker has been doing since the ending of the artificial conditions of war time. I propose to outline first some of the more recent developments in materials and processes and then to show the impact these have had on cable design and construction.

Materials and Processes

As a conductor, copper remains virtually unchallenged and, except for features such as compacted strands and conductor screening, substantially unchanged for general cable use, although for certain high-temperature applications conductors are electroplated with nickel or silver.

Aluminium, with its relative lightness, low cost and reasonable conductivity, is at first sight attractive, and certain of its uses are well established. Technically, its wider application presents no difficulties, and cablemakers are ready to employ it. Its ultimate scale of use depends on relative costs, which must include the greater volumes of insulating and protective materials required for aluminium conductors compared with those for the copper equivalent.

With rubber, the main advances have been in manufacturing techniques, such as improvement in extrusion machines and the increasing adoption of continuous vulcanization. Conducting rubber is being explored, in place of metallic wires, for the screens of colliery trailing cables; and rubber-insulated cables are protected from ozone and oil by a thin external layer of synthetic rubber.

Of the many synthetic materials developed abroad, only polychloroprene is in extensive use; its properties make it valuable as a cable-sheathing and protective covering in aircraft, mining and other spheres. Silicone rubber, with its high heat resistance and flexibility at low temperatures, is employed in aircraft wiring.

The war-time developments of plastics have been pursued further, giving the cablemaker a wide range of materials not available in any substantial form in pre-war days.

Polyvinylchloride (p.v.c.) and its co-polymers give a variety of insulating and sheathing compounds, easy to process and characterized by toughness, flexibility and resistance to many solvents and to burning.

Polyethylene, available in several grades with differing physical properties, has low moisture absorption and outstanding electrical characteristics for high voltages and high frequencies. It calls for special precautions in processing and use to counter the effects of exposure to heat, to sunlight and to contact with a variety of other materials.

Polystyrene, also with low moisture absorption and excellent electrical properties, has a tendency to brittleness, which is overcome by using orientated tapes to form laminated dielectrics.

Polytetrafluoroethylene (p.t.f.e.), chemically and physically stable, has many of the virtues of polyethylene and unique qualities for high temperatures up to 250°C, such as for aircraft wiring. It is costly. Fabrication demands special processing techniques, and high-temperature uses require conductors of nickel, silver or plated copper.

Nylon has toughness which renders it valuable for sheathing, extruded or as a textile braid.

In papers and compounds for mains cables, the significant developments since pre-war days have been in the quality and choice of materials.

Improved wood-fibre papers have largely replaced the earlier-favoured manila and manila-wood papers. The petroleum refiners have made available much-improved grades of hydrocarbon oils. Established precautions against migration of fluid compounds on gradients are now supplemented by a method of mass-impregnation employing an impregnant which, though fluid at cable manufacturing temperatures, is a plastic solid up to temperatures higher than those of service.

The post-war scarcity of lead stimulated the search for alternative materials of lower density and greater mechanical strength.

The lightness, strength and high fatigue resistance of aluminium make it an obvious choice for cable sheathing. It makes armouring unnecessary for most uses and obviates the need for reinforcement in pressurized cables. Satisfactory corrosion protection has been evolved, and jointing techniques are well established. In this country, most experience is with sheaths made by the "tube-sinking" process of pulling the cores into an oversize tube which is subsequently drawn down to the desired diameter. Alternatively an over-size sheath may be formed from longitudinal strip, argon-arc welded, the sheath then being drawn down to size and helically corrugated to improve its flexibility. Direct extrusion, although attractive, presents difficulties because of the high temperatures and pressures involved. Much work has been done in this development, both here and on the Continent. One British cablemaker has installed an extrusion press, using solid billets and operating at a reasonably low temperature, which gives promise of the satisfactory production of aluminium-sheathed cables in long continuous lengths.

A number of composite-sheath constructions have been evolved for telephone cables, to provide a moisture seal and resistance to corrosion. An example is the American sheath, embodying aluminium and steel strip and covered with extruded polyethylene. Thin lead sheaths with an outer layer of polyethylene are expected to find increasing use.

A significant development in protection materials is the replacement of impregnated textile servings by tapes of self-sealing rubber and p.v.c. to reduce the danger of water absorption.

Impacts on Cable Design and Construction

Recent developments in telecommunication cables have made full use of plastics, leading not only to the replacement of established types of insulant on technical or economic grounds, but also to the evolution of new types of cable with very exacting

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transmission characteristics, for telecommunication, radio and electronic equipment.

In switchboard wiring, coloured and striped p.v.c. is tending to replace the widely-used enamel and textile coverings.

It is significant that in the first 40 years of this century, frequencies to be transmitted by cable advanced a thousandfold from 3×10^4 to 3×10^7 c/s, and that during the succeeding decade they rose to 3×10^{10} c/s, a further thousandfold increase. Only polyethylene and polystyrene, with their low loss factors, could meet the requirements of long-distance and high-frequency transmission. Even these materials would have been inadequate had it not been for the concurrent development of new techniques to give precise dimensions and of new electronic test-gear.

Polyethylene, the more easily handled material, is widely used. As a solid extrusion it is being introduced for telephone distribution cables. Radio-relay and television-relay cables have polyethylene insulation and sheaths; they are light in weight, and have low transmission losses and high moisture resistance. Polyethylene insulation is being employed for quad-type carrier telephone cables; on the Continent, polystyrene string and tape constructions have been adopted for this purpose; and experiments are being made in America with cellular polyethylene. The conventional television down-lead cables are polyethylene insulated: for the higher frequencies in Band III of the coming commercial programmes an expanded polyethylene insulant has been introduced.

A notable use of plastics is in the spaced-disc coaxial pairs developed for multi-channel telephony or television signals. A classic example is the 1 in coaxial cable forming the London–Birmingham television link, and many hundreds of miles of $\frac{3}{8}$ in coaxial pairs are in regular use, both at home and abroad, operating on frequencies up to 10 Mc/s and providing up to 600 speech channels.

The recently-announced transatlantic telephone cable is the first project of such magnitude to be undertaken anywhere in the world: it is to have solid polyethylene insulation of thickness and precise dimensions which the recent advances in technique have alone made feasible.

Polystyrene in the form of multiple tapes applied in an open helix is used for several cables of coaxial type up to $3\frac{1}{8}$ in diameter, employed for high-power high-frequency links. There are numerous radio-frequency cables with solid or semi-air-spaced polyethylene insulation.

Television cameras require multiple connections for video frequencies up to many megacycles per second, for audio signals and for power and control circuits. These complex cables must be small, flexible, rugged and weatherproof, and must be easily capable of extension. Accurately extruded thin polyethylene coverings on small conductors, and a special connector moulded to the cable, have met these requirements.

For lighting and low-power cables, increasing use is made of rubber-insulated tough-rubber-sheathed cable. Advances in technique have permitted reductions in diameter of many types of cable, as reflected in B.S. 7: 1953. The use of p.v.c. wiring cables is growing, with emphasis on conduit wiring. B.S. 1557, for polyethylene-insulated and p.v.c.-sheathed types, has just been revised.

Aircraft cables provide a good illustration of the exploitation of the special properties of plastics, in that light weight, resistance to solvents and a wide temperature range of operation are essential.

The insulation of pre-war aircraft cables was rubber, protected by a lacquered cotton braid. This has in late years been replaced by glass-fibre braid and a polychloroprene sheath, with a saving of 50% in weight and a wider temperature range.

For the extreme temperatures encountered in jet aircraft combinations of p.t.f.e. and glass-fibre braid, though costly, give outstanding performance, and the pre-war operating range of $-10°$ to $+70°$C has thus been extended to $-75°$ to $+400°$C.

Broadly speaking, paper-insulated cables continue to hold the field for power supply. Cables with plastic insulation and sheath have proved satisfactory in performance in the lower-voltage range. They are attractive because of light weight and simplicity of jointing. In countries where skilled jointers are available any marked extension in their use seems likely to turn on relative costs.

In the very-high-voltage field, the post-war years have seen a notable extension in the use of higher voltages, for which there has been an accentuated swing to the use of pressurized cables. The higher operating stresses and temperatures and increased circuit capacity of these cables are reflected in the lower cost of an installation; and this, coupled with the fact that they are essential for voltages over 66 kV, is responsible for the greatly increased demand. Pressurized cables are of four main types, namely:

Oil-filled cables, which are impregnated with low-viscosity oil and embody channels to permit longitudinal oil-flow to or from reservoirs. The static operating pressure is normally 75 lb/in². A later variant, in which the three cores are laid side by side within a flat-sided sheath, enables reservoirs to be dispensed with, the cable being "self-compensating."

Gas pressure cables, which are subject to internal gas pressure of 200 lb/in², and are of two sorts. In the *gas-filled cable*, the dielectric is formed from pre-impregnated paper tapes, the gas filling the interstices between tapes to form a composite dielectric. *Impregnated pressure cables* are fully impregnated, the gas being accommodated in under-sheath clearances.

Compression cables, which consist essentially of solid-type cables covered by a thin lead diaphragm and enclosed in an outer sheath or pipe. The space between diaphragm and pipe is charged with gas, the pressure of which is transmitted to the cables via the diaphragm.

Pipe cables, which are oil-impregnated solid-type cables without sheaths, and are drawn into a steel pipe containing oil or gas under pressure.

Although 220-kV oil-filled cables were installed in Paris in 1936, there has in the past been no general call in this country for cables for voltages above 132 kV. However, since the 275 kV system now under erection will eventually require cables for that voltage, the B.E.A. and cable manufacturers have collaborated in the installation of trial lengths of 275 kV pressurized cables.

Cables for even higher voltages have been made for two installations abroad. For the Kemano project in Canada, two runs of 301 kV oil-filled cable have been laid, one having aluminium conductors and sheaths; while in Sweden a 380 kV cable of the oil-filled type has been installed.

Another post-war trend is towards the use of high-voltage submarine crossings. A project has been worked out for a 132 kV cable, crossing the Channel, to link the British and French systems, and sea trials have been made, using gas-filled and compression cables.

In Canada, a British cablemaker is shortly to install an 18-mile underwater link, between British Columbia and Vancouver Island, consisting of 138 kV gas-filled cables.

This is the picture as I see it. It may not be comprehensive or balanced, but I hope I have given an impression of the cablemaker's activities. The work continues; and I have no doubt some future Chairman, choosing the same topic, would find ample new material for his Address.

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Paper No. 1744
Nov. 1954

THE ELECTRIFICATION OF THE MANCHESTER–SHEFFIELD–WATH LINES, EASTERN AND LONDON MIDLAND REGIONS, BRITISH RAILWAYS

By J. A. BROUGHALL, B.Sc.(Eng.), Member, and K. J. COOK, O.B.E., M.I.Mech.E.

(*The paper was first received* 4*th June, and in revised form* 27*th July*, 1954. *It was published in November*, 1954, *and was read before* THE INSTITUTION 2*nd December, and the* NORTH-WESTERN CENTRE 7*th December*, 1954, *the* RUGBY SUB-CENTRE 15*th February, the* MERSEY AND NORTH WALES CENTRE 21*st February, the* NORTH-EASTERN CENTRE 28*th February, the* SOUTH-WEST SCOTLAND SUB-CENTRE 23*rd March, and the* SOUTH-EAST SCOTLAND SUB-CENTRE 5*th April*, 1955.)

SUMMARY

The paper briefly describes the lines of British Railways from Manchester to Sheffield and to Wath, which have recently been electrified on the 1 500 volt overhead d.c. system.

After analysing the nature of the traffic, it describes the schemes for electrification since their inception before the 1939–45 War, which stopped the work after design and manufacture had commenced.

It then describes the electrification, noting the similarities in design with corresponding features of the Liverpool Street–Shenfield electrification, which had a rather similar history associated with special priority in the post-war period.

The $B_0 + B_0$ and C_0–C_0 locomotives are described in some detail.

Particulars are given of the limited operating experience so far obtained, particularly on the line to Wath, on which freight traffic has been electrically hauled since February, 1952.

The paper mentions the use of new constructions and discusses the possibility of extending the electrification and the probability that to do so would be relatively less expensive and more rewarding than the present scheme.

(1) INTRODUCTION

The Manchester–Sheffield–Wath line is the first main line in this country on which freight traffic predominates to be electrified. The work, which started in 1938, has been grievously hindered by the war, by post-war shortages and other factors.

On the section to Wath, all freight traffic has been electrically hauled since February, 1952. On the main line, Manchester to Sheffield, all trains have been hauled electrically west of Penistone since the 14th June, 1954. The full service between Manchester and Sheffield was inaugurated on the 14th September, 1954, and the final extension East to Rotherwood was completed by the 3rd January, 1955.

(1.1) History and Description of the Lines

The railway line from Sheffield (Victoria) to Manchester (London Road), authorized by Act of Parliament in 1837, was built by the Sheffield, Ashton-under-Lyne and Manchester Railway, and opened to through traffic on the 23rd December, 1845. As shown in Figs. 1 and 2, it passes over the Pennine Range; the summit (960 ft above sea level) was pierced between Dunford and Woodhead by two single-line tunnels, 3 miles long. It is characterized by long steep gradients on both sides. On the Sheffield side, the approach is by gradients averaging 1 in 127 for 19 miles; on the Manchester side, there are $22\frac{1}{2}$ miles at gradients averaging 1 in 147. On both sides, the ruling grades are 1 in 100. The line is almost continuously curved, little more than 10% being on straight track.

The line from Barnsley Junction to Wath was built by the Great Central Railway and is even more steeply graded and badly curved. The heaviest grade is the 1 in 40 Wentworth Bank, 2·2 miles in length.

Both lines became part of the Great Central Railway; in 1923 of the London and North Eastern Railway, and in 1947 of the Eastern Region of British Railways, but during the course of the electrification the line west of Thurlstone became part of the London Midland Region.

There are four tracks for six miles from Manchester to Hyde Junction and most of the way between Hadfield and Woodhead. Elsewhere there are generally two tracks, with a considerable stretch of additional "down" track between Thurlstone and Bullhouse. At both ends of the line there are extensive marshalling yards and sidings, so that although the route mileage electrified is 68 miles, the single-track mileage of running lines is 212 miles and of sidings 88 miles. A further impression of the complexity of the lines is given by the fact that there are 443 signals needed to control the traffic—over 2 per single-track-mile of running lines.

Many parts of the line are subject to subsidence owing to colliery workings and to pollution from coke-oven plants, etc.

(1.2) Traffic on the Lines

These lines are among the most important East and West freight routes in the country, connecting the Sheffield, East Midlands and South Yorkshire coalfields and industrial areas with those of Manchester and Merseyside. There are approximately 80 "down" freight trains per day to the marshalling yards at Mottram, Godley and Guide Bridge. In the west to east ("up") direction, the traffic is lighter, about 60 trains per day, the bulk of the loaded wagons going to Sheffield and empty coal wagons to Wath. The passenger service between Manchester and Sheffield comprised 14 trains per day in each direction, prior to electrification.

There is suburban traffic between Manchester and Hadfield on the main line and to Glossop on a branch. There are local trains from Sheffield to Penistone.

The volume of traffic can be expressed as approximately 4 700 000 trailing ton-miles per mile of single-track running lines per annum.

Because of the physical difficulties of the line already described, it had always been difficult to handle this great traffic effectively. On the Wentworth Bank, four steam engines were needed, two hauling and two banking, to handle a 1 074-ton train, although one could be dispensed with when the Garratt locomotive specially built for this service was available. As most of the freight trains comprise loose-coupled wagons not fitted with a continuous brake, it was customary to stop at the summit of severe grades and drop or pin down brakes on a high proportion of the wagons.

The poor ventilation, the gradient and latterly the general deterioration of the condition of the 100-year old tunnels formed another traffic bottleneck.

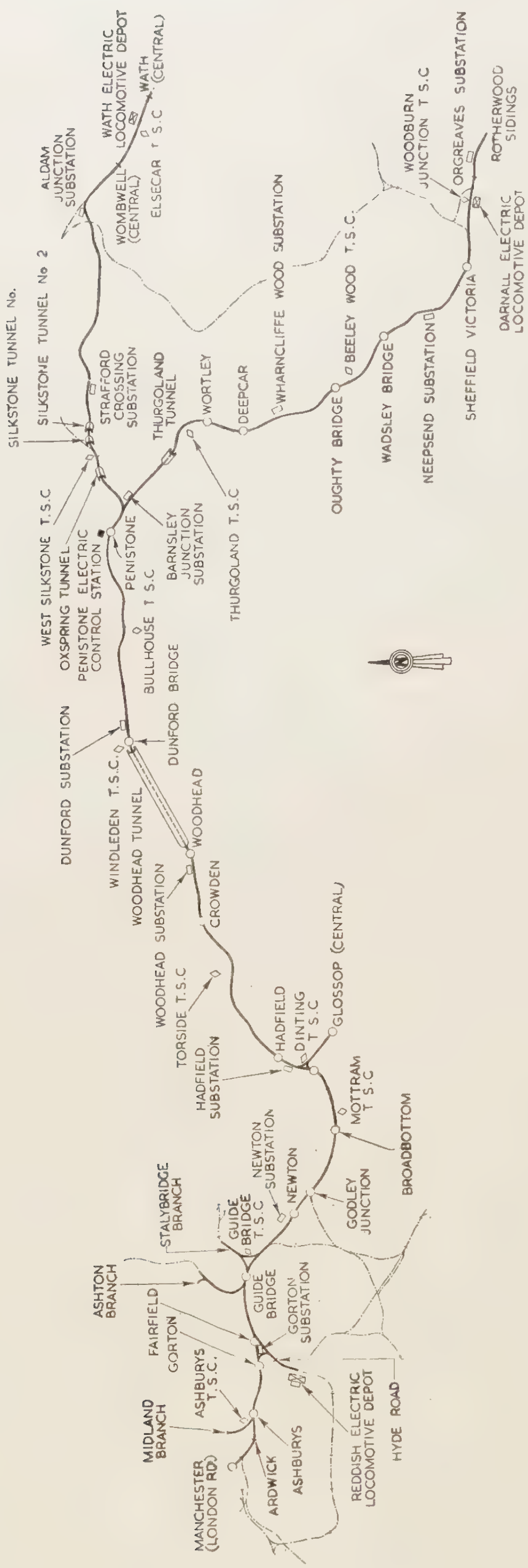
(2) THE ELECTRIFICATION SCHEMES

(2.1) Pre-War Schemes

Investigations into the merits of electrification of a short section were made by the G.C.R. and extended by the L.N.E.R., leading

This is an "integrating" paper. Members are invited to submit papers in this category, giving the full perspective of the developments leading to the present practice in a particular part of one of the branches of electrical science.

Mr. Broughall and Mr. Cook are with British Railways.



to the production of a favourable report in 1926, but circumstances did not permit authorization. In October, 1936, however, the L.N.E.R. Board authorized electrification and Government assistance was given under the scheme to assist unemployment.

After consideration of alternatives, it was decided to adopt the 1 500-volt d.c. overhead system with regenerative braking, surplus power being absorbed in resistors at some substations to avoid the complication of reversible converting plant.

This plan is the basis from which all later schemes stem. Contracts were placed in 1938/39. At this stage it was intended to retain the old tunnels at Woodhead, the open-wire telephone circuits, the semaphore signals, and the steam shunting locomotives. Provision was made for a stock of 88 electric locomotives and 41 40-ton vacuum-fitted goods brake vans. Freight trains were to weigh up to 1 074 tons.

As existing route plans were inadequate, an aerial survey was made in 1938 from which detail plans were prepared. The scheme was estimated to cost £3 000 000 and to give a net return, after allowing for interest and depreciation, of 4·4% and to save 100 000 tons of coal per annum.

Considerable progress was made with provision of foundations and erection of steelwork for the overhead contact system, and by the time the work was stopped in 1940, work to the value of about £750 000 had been done. One $B_0 + B_0$ locomotive had been built and was tested on the Manchester South Junction and Altrincham line in 1941. This locomotive was used in Holland after the war, rendering useful service to the Netherlands Railways during their post-war shortage of rolling stock. Designs were also completed by contractors for other sections of the work and considerable quantities of material were purchased and partly manufactured.

(2.2) Post-War Variations

A Railway Committee, in 1944, modified the scheme to get fuller benefit from the enhanced expenditure which post-war conditions would obviously entail, and to take account of other altered operational circumstances. For example, it had become

Fig. 1.—Electrified lines.

——— Manchester–Sheffield–Wath electrified lines.
– – – – Other lines.
T.S.C. — Track-sectioning cabin.

Substation and track-sectioning cabin mileages

From	To	Miles
Main Line		
London Road station	Ashburys T.S.C.	1·57
Ashburys T.S.C.	Gorton substation	1·59
Gorton substation	Guide Bridge T.S.C.	2·46
Guide Bridge T.S.C.	Newton substation	1·79
Newton substation	Mottram T.S.C.	3·49
Mottram T.S.C.	Hadfield substation	1·97
Hadfield substation	Torside T.S.C.	2·70
Torside T.S.C.	Woodhead substation	3·82
Woodhead substation	Windleden T.S.C	3·15
Windleden T.S.C.	Dunford substation	0·96
Dunford substation	Bullhouse T.S.C.	2·56
Bullhouse T.S.C.	Barnsley Junction substation	3·44
Barnsley Junction substation	Thurgoland T.S.C.	2·81
Thurgoland T.S.C.	Wharncliffe Wood substation	2·59
Wharncliffe Wood substation	Beeley Wood T.S.C.	2·42
Beeley Wood T.S.C.	Neepsend substation	2·99
Neepsend substation	Woodburn Junction T.S.C.	2·73
Woodburn Junction T.S.C.	Orgreaves substation	2·35
Orgreaves substation	Rotherwood (end of wiring)	1·04
Wath Branch		
Barnsley Junction substation	West Silkstone T.S.C.	1·40
West Silkstone T.S.C.	Strafford Crossing substation	2·65
Strafford Crossing substation	Aldam Junction substation	4·69
Aldam Junction substation	Elsecar T.S.C.	2·13
Elsecar T.S.C.	Wath	1·49
Glossop Branch		
Dinting T.S.C.	Hadfield substation (main line)	0·64
Dinting T.S.C.	Glossop	0·99

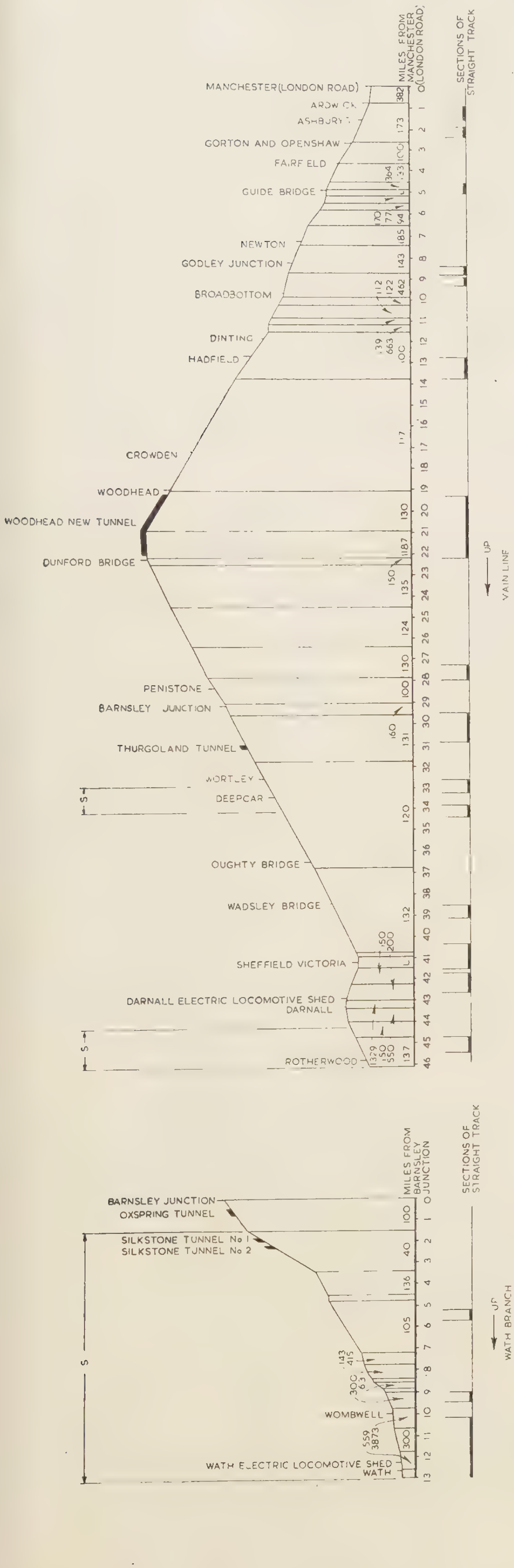


Fig. 2.—Gradient profiles.
S.—Areas subject to mining subsidence.

desirable to arrange for out-and-home working for locomotive crews so as to avoid their having to lodge away from home. This demanded faster and therefore lighter trains and the repositioning of signals to give longer stopping distances (1 200yd). It was decided to work 750-ton freight trains with a single electric locomotive from Rotherwood to Dunford and 850-ton trains with one banker from Wath to Dunford, and to work both these loads through to Manchester with a single locomotive dispensing with the 40-ton brake vans. This implied a considerable increase above the duty for which the locomotives were designed. It was also decided to build a new tunnel at Thurgoland, the clearances in the old one having been found inadequate, and that all distant signals should be colour lighted.

The resumption of work was authorized in 1946 at a revised cost of about £6 200 000.

Almost simultaneously, the resumption of work on the Liverpool Street–Shenfield electrification was authorized and given priority. Thus, it was not until 1949 that work was resumed on the Manchester–Sheffield–Wath electrification.

Meanwhile, after attempts to repair the old Woodhead tunnels had failed in 1946, it was decided in 1947 to construct a new double-line tunnel. This had a major influence on the timetable for the electrification. Work on the tunnel started in February, 1949, and was completed in August, 1953.[1]

The Railway Executive assumed responsibility for the scheme in 1947; following a review of the proposals in the light of rising costs, the electrification of the lines from Reddish to Manchester Central and Trafford Park was postponed, and the accommodation at Reddish Depot was reduced. The final scheme provided for 58 $B_0 + B_0$ locomotives and for 7 C_0–C_0 locomotives.

The estimated cost of the scheme became £10 877 000 made up as follows:

Electrical engineering work	£6 754 000
Mechanical engineering work	£1 020 000
Civil engineering work	£1 590 000
Signal and telecommunication work	£1 513 000

It was subsequently decided to replace all signals, except those between Ardwick and Manchester (London Rd.), by colour lights and to put all communication circuits into cable.

Table 1 gives salient particulars of the services to be provided. The improvement in speed of freight trains will be much greater than is shown by the comparison in booked times because the punctuality of freight trains should be much better than was ever possible under steam operation. Large improvements in passenger-train speeds are impracticable because the whole line is subject to a speed limit of 65m.p.h. and there are numerous speed checks due to curvature of the track and mining subsidence.

(3) CO-ORDINATION OF WORK

Since May, 1950, the New Works and Development Section of the Railway Executive, and later of the British Transport Commission, has been responsible for electrical engineering work up to the point of commissioning for service, when the responsibility for operation passes to the Chief Mechanical and Electrical Engineer of the Eastern Region, who has also built the mechanical parts of the locomotives.

Many departments of the Eastern and London Midland Regions have been concerned in the planning and execution of the work, principally the Operating Department (E.R.), who schemed traffic to allow construction to proceed; the Motive Power Superintendent (E.R.), who has released steam-locomotive drivers for training; the Signal and Telecommunication Engineers (E.R. and L.M.R.), who, in addition to the signalling changes mentioned, have had to change their track circuits

Table 1

COMPARATIVE TRAIN TIMINGS

Class of train	From	To	Steam	Electric
			min	min
Down Trains				
Express passenger	Sheffield (Victoria)	Manchester (London Road)	70	56
Multiple-unit	Glossop	Manchester (London Road)	37	32
Express freight	Sheffield (Bridgehouses)	Manchester (Ducie Street)	86	69
Mineral	Woodburn Junction (Pass)	Mottram Yard	138	81
Mineral	Wath Yard	Mottram Yard	162	97
Up Trains				
Express passenger	Manchester (London Road)	Sheffield (Victoria)	68	56
Multiple-unit	Manchester (London Road)	Glossop	39	34
Express freight	Ardwick (East)	Sheffield (Bridgehouses)	87	69
Goods	Ashburys West	Woodburn Junction (Pass)	154	101
Empties	Dewsnap Yard	Wath Yard	177	86

Note:—The electric service between Manchester (London Road), Hadfield and Glossop is a ½-hour interval service between 5.15 a.m. and 7.45 p.m.; then hourly to 10.45 p.m., and trains are increased from 3 to 6 coaches during the rush periods.

from direct to alternating current and clear obstructions in advance of the erection and testing of overhead equipment; and finally the Civil Engineers (E.R. and L.M.R.), who, in addition to the tunnel works mentioned, have constructed substations, control rooms, depots, etc., lifted bridges or lowered tracks to give clearance, and done much other work in connection with the modernization of this section of the Railway.

All this work has proceeded with the minimum interference to the heavy flow of traffic over the line. That the sections of the work have so far been commissioned on or in advance of the planned dates is due to the close and friendly co-operation of all departments of both Regions and of the contractors concerned. It has necessitated much expensive and difficult night and Sunday work, often under conditions amounting to hardship for the staff on the line.

(4) DESCRIPTION OF FIXED EQUIPMENT

The basic design of all the work corresponds more closely to the practice of 1936 than to that of to-day, and there are many similarities with the equipment used for the Liverpool Street–Shenfield electrification.[2] Reference is only made herein to equipment differing from that used on the suburban electrification mentioned, and to some methods incorporated on a small scale to reduce costs without unduly impairing overall efficiency.

(4.1) Power Supply

In implementation of plans agreed with the former supply companies and corporations, energy is obtained from the British Electricity Authority at 33 kV at three supply points as follows:

Aldam substation from Yorkshire Electricity Board.
Gorton substation from North Western Electricity Board.
Neepsend substation from Yorkshire Electricity Board.

These are interlinked, and arrangements have been made for using alternative sources in the event of cable or supply failures and for summation of maximum demand between all points of supply.

At Neepsend and Gorton, there is a measure of joint user of the 33 kV switchgear with the Electricity Board, and provision has been made for this to develop as circumstances require, the railway substations forming part of the Board's ring main.

At Aldam substation two 66/33 kV transformers of 5 MVA have been installed to give the railway supply from the adjacent Electricity Board substation.

Provisional tariffs are at present in force pending completion of regulations to be made by the Minister of Fuel and Power and the Minister of Transport.

Table 2

ESTIMATED ANNUAL ENERGY CONSUMPTION AND MAXIMUM DEMAND WITH ELECTRIFICATION IN FULL OPERATION

Aldam		Neepsend		Gorton	
Maximum demand	Energy consumed	Maximum demand	Energy consumed	Maximum demand	Energy consumed
kW	kWh × 10^6	kW	kWh × 10^6	kW	kWh × 10^6
5 230	21·45	4 760	19·75	6 560	31·0

Table 2 gives particulars of the estimated annual consumption and of maximum half-hour demand in normal circumstances on completion of the scheme.

(4.2) Transmission System

Fig. 3 shows the railway-owned high-voltage feeder network and the main components of substation and of track-section-cabin equipment. It will be noted that, in accordance with standard British Railways practice, all eleven substations and twelve track-section cabins operate in parallel on the d.c. side.

The 33 kV feeders are 3-core H.S.L. S.W.A. cables supported by hangers from concrete posts, except where local conditions necessitate the use of hangers on walls, etc., or of reinforced concrete troughing. In areas liable to mining subsidence, the cables are housed in protected steel troughing mounted on tall posts so that the route can be adapted to settlement of the ground.

(4.3) Substations and Track-Sectioning Cabins

(4.3.1) **General.**

The general arrangement of the substations with their outdoor 33kV switchgear rafts follows very closely that of the Shenfield electrification, and reference may be made to Fig. 3 of Mr. Swift's

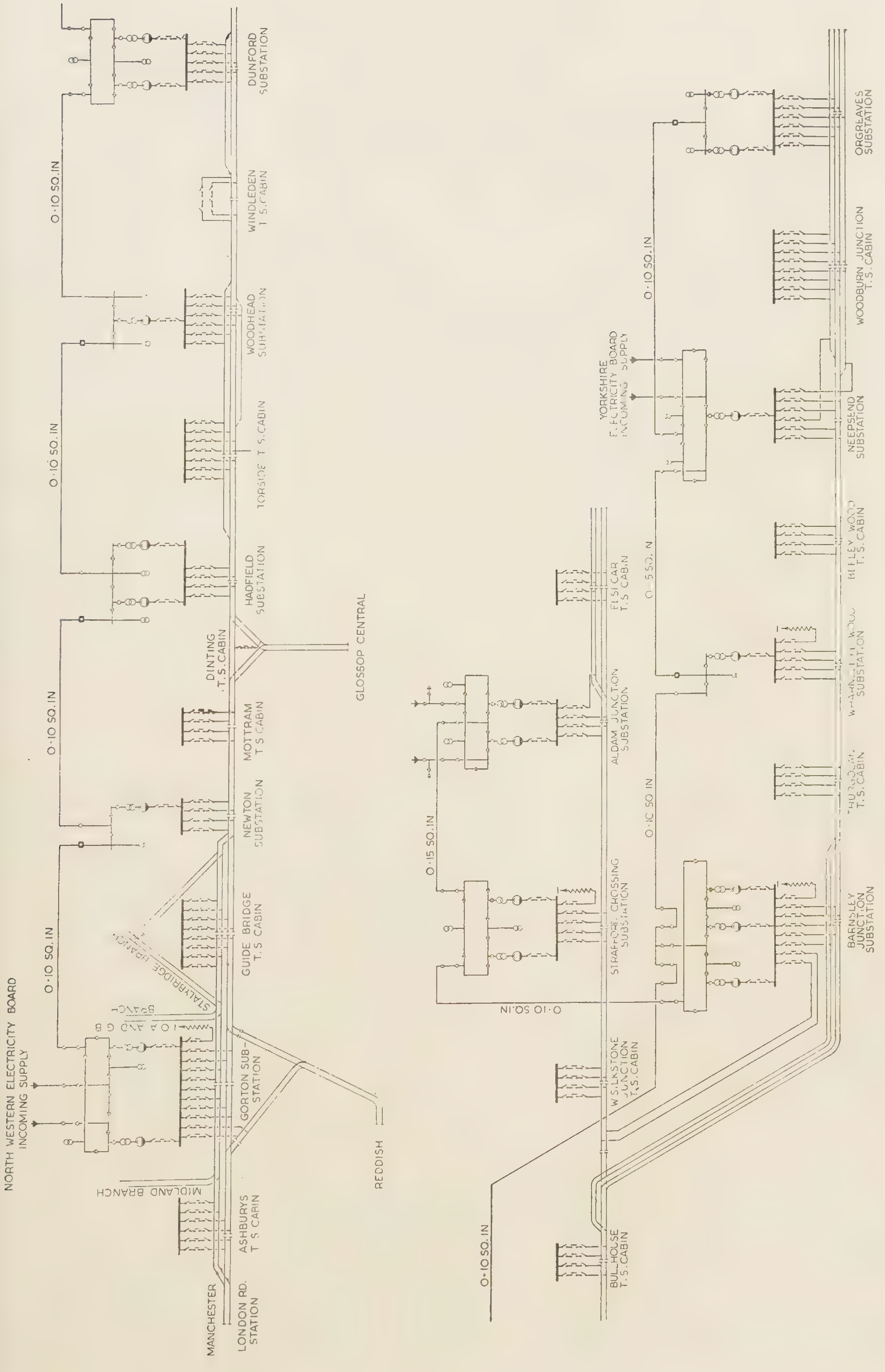


Fig. 3.—Schematic of high-voltage and d.c. connections for substations and track-section cabins.

Rectifier . . . H.V. isolators . . .
Rectifier transformer . H.V oil circuit-breakers . .
Auxiliary transformer . . H.V. power-operated isolators .
Regeneration resistors .

Table 3

MAIN ITEMS OF EQUIPMENT OF SUBSTATIONS AND TRACK-SECTION CABINS

Substation or track-sectioning cabin	2 500kW rectifier units		Switchgear				No. of 1 500V d.c. high-speed circuit-breakers		
	No.	Total kW capacity	Incoming supply o.c.b.'s	Feeder o.c.b.'s	Power-operated isolators	Rectifier o.c.b.'s	Feeder or track sectioning	Rectifier	Regenerative loading
Substations									
Gorton	2	5 000	2‡	1	—	2	10	2	1
Newton	1	2 500	—	1	1	1	4	1	—
Hadfield	2	5 000	—	1	1	2	4	2	—
Woodhead	1	2 500	—	1	1	1	6	1	—
Dunford	2†	5 000	—	2	—	2	5	2	—
Strafford Crossing	2†	5 000	—	2	—	2	4	2	1
Aldam	2†	5 000	2	1	—	2	4	2	—
Barnsley Junction	3†	7 500	—	4*	—	3	7	3	1
Wharncliffe Wood	1	2 500	—	1	1	1	4	1	1
Neepsend	1	2 500	2‡	2	—	1	6	1	—
Orgreaves	2	5 000	—	—	1	2	6	2	—
Track-sectioning Cabins									
Ashburys	—	—	—	—	—	—	6	—	—
Guide Bridge	—	—	—	—	—	—	8	—	—
Mottram	—	—	—	—	—	—	4	—	—
Dinting	—	—	—	—	—	—	1	—	—
Torside	—	—	—	—	—	—	7	—	—
Windleden	—	—	—	—	—	—	2	—	—
Bullhouse	—	—	—	—	—	—	4	—	—
West Silkstone	—	—	—	—	—	—	4	—	—
Elsecar	—	—	—	—	—	—	4	—	—
Thurgoland	—	—	—	—	—	—	4	—	—
Beeley Wood	—	—	—	—	—	—	4	—	—
Woodburn Junction	—	—	—	—	—	—	8	—	—
Totals	19	47 500	6	16	5	19	116	19	4

o.c.b.—oil circuit-breaker.

* Including 1 busbar section oil circuit-breaker.
† Water-cooled type.
‡ Electricity Board's oil circuit-breakers.

paper[2] for a layout of a typical ring-main substation. Table 3 gives particulars of the main items of equipment in each substation and track-sectioning cabin.

(4.3.2) **H.V. Switchgear.**

In five substations constructed after 1951, some economy was obtained with a little loss of flexibility but without prejudice to reliability or to later extensions, by a limited use of power-operated isolators and a straight-line busbar. All apparatus is suitable for a short-circuit duty of 500MVA, except at Gorton, where 750MVA gear is installed. The oil circuit-breakers have three phases in one tank and are motor-wound spring-operated.

Solkor pilot-wire balanced protection is used with back-up overload protection matched with the Electricity Board's equipment. The rectifiers are protected on the a.c. side by instantaneous overload and earth-leakage relays.

(4.3.3) **Auxiliary Services.**

Duplicate auxiliary transformers, protected by h.r.c. fuses, give normal supplies to signal circuits through contactors arranged to maintain supply if one source fails. In addition, standby Diesel-driven generators have been installed—70kVA at Gorton and 25kVA at Aldam—to cut in automatically on drop of voltage or frequency.

(4.3.4) **Rectifiers.**

Rectification from alternating to direct current is by 12-phase mercury-arc rectifiers. At 4 substations these are of the 12-anode water-cooled continuously-pumped type originally ordered in 1938 and partly manufactured before the war. At the other 7 substations they are of the later air-cooled type with two cylinders per equipment, each with 6 anodes, continuously pumped as advocated by the contractor concerned.

All transformers are similar and all rectifiers are rated at 2·5MW (nominal) but capable of the following duty cycle determined by estimates of the most arduous service conditions:

1. Full load (1 666amp) for 15min.
2. 3 × full load (4 998amp) for 1min.
3. 65% full load (1 090amp) for 14min.
4. 4 × full load (6 664amp) for $\frac{1}{2}$min.
5. 81% full load (1 350amp) for $14\frac{3}{4}$min.
6. 3 × full load (4 998amp) for 1min.
7. 65% full load (1 090amp) for 14min.
8. 2 × full load (3 332amp) for 5min.
9. 65% full load (1 090amp) for 25min.
10. 3 × full load (4 998amp) for 1min.

Repeat items 3–10 immediately.

Followed by 65% full load (1 090amp) for 10 hours with the load increased to 3 × full load (4 998amp) for the last minute of each 15min period.

Repeat items 3–10 twice.

Total time of test: 15 hours, 16min.

The transformers are of the ON type with detachable radiators. Primary windings are delta connected and have off-load tappings for $\pm 2\frac{1}{2}\%$, $\pm 5\%$, $-7\frac{1}{2}\%$ and -10%.

The secondary windings comprise 4 zigzag-connected sections to give a 12-phase supply. A 150c/s choke is connected between the neutral point of each of the two pairs of zigzag sections, and

the mid-points of the 150c/s chokes are connected via a 300c/s choke. The mid-point of the 300c/s choke forms the point of connection of the d.c. negative. Filter circuits to reduce the 600, 900 and 1 200c/s harmonics are installed.

(4.3.5) **Direct-Current Switchgear.**

The high-speed circuit-breakers, although of a different make, and a negative earthing device are arranged in the same manner as those described for the Shenfield electrification.

(4.3.6) **Regeneration Resistors.**

Regeneration resistors are installed at four strategically placed substations, namely Strafford Crossing, Barnsley Junction, Gorton and Wharncliffe Wood.

Each equipment has a continuous rating of 600amp at 1 500 volts (nominal) and comprises four banks of resistors each cooled by a motor-driven fan which starts up when the equipment is switched on to the line. The availability of regenerated energy is detected by the increase of voltage in a circuit in which a potential difference from a voltage divider supplied at line voltage is opposed to a fixed potential difference on the grids of a thyratron associated with each bank of resistors.

When the appropriate value is reached, each thyratron excites an ignitron, the firing of which closes the contactor, cutting out the ignitron and connecting the resistor to the line. Switching out is done by four timing relays which de-energize the contactors in turn, if the regenerated current has decreased by the appropriate amount.

The arrangement of these circuits is shown in Fig. 4.

As shown in Fig. 5, the control-room plan and elevation differ considerably from the layout adopted at Chadwell Heath, principally to conform to the physical features of the site.

(4.5) Overhead Line Equipment

(4.5.1) **General.**

The overhead equipment generally follows closely the design described for the Shenfield electrification. The total normal cross-section is equivalent to $0\cdot75\,in^2$ of copper over each running line and to $0\cdot36\,in^2$ sidings. Cadmium-copper contact wire is used throughout, the section corresponding to Fig. 1 of B.S. 23 on running lines.

(4.5.2) **Special Construction for Supports.**

Except on the actual crossing of the Pennines, where a high proportion of the structures are of the broad flange beam portal type spanning 2 or 4 tracks, a large number of special types were needed to suit the complicated layout of the lines at junctions and in yards. The complexity of this work is reflected in the fact that approximately 8 000 tons of main structural steelwork was required for equipping 300 single-track-miles and that over 500 different designs of structure, many with varying lengths of boom and masts, were required for a total of 3 460 structures.

Particulars of some of these special structures and of the additional costs they involved have been given by Crompton and Wallace.[3] This paper also describes some of the possibilities of cheapening the cost of construction evolved jointly by the contractors concerned and the Railway's engineers.

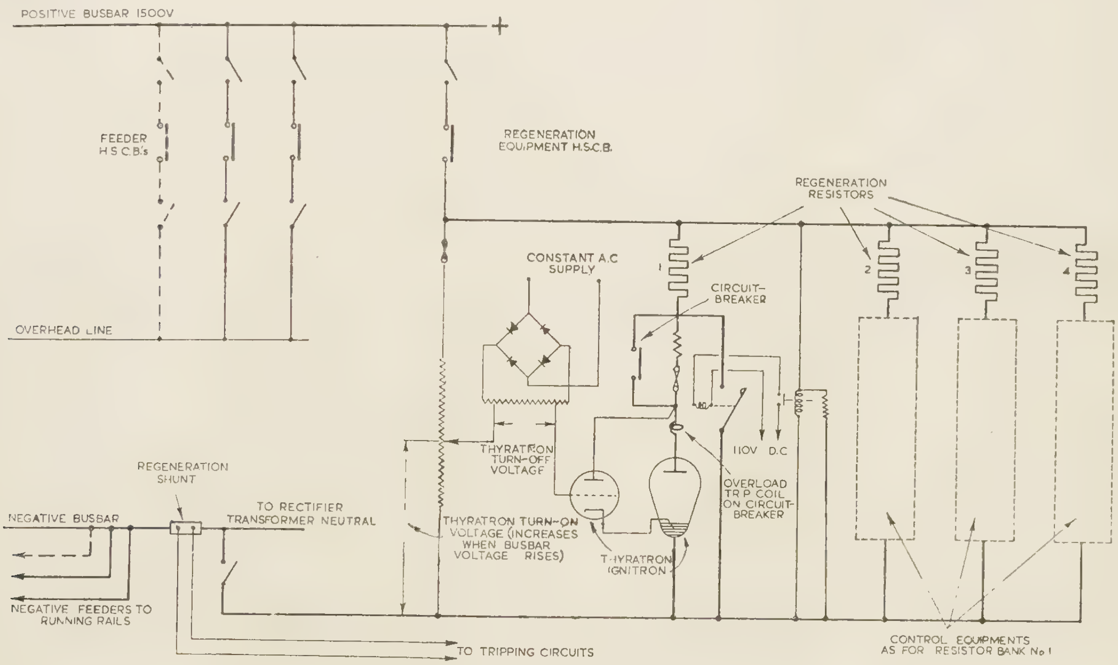


Fig. 4.—Schematic of regeneration loading circuits.

(4.4) Supervisory Control

Substations and track-sectioning cabins are unattended and remotely controlled from Penistone electric control room by apparatus of the telephone type, using a common-diagram method of control and indication similar to that in use on the Shenfield electrification. A total of 173 controls may be made and 224 indications received at the control room, which is designed to accommodate additional equipment for the control of a further 15 substations.

Experimental use of these and some other modified constructions is being made on this electrification.

In particular, reference may be made to the following:

(*a*) On a section of about 1 mile in length, the stitched wire or Y-construction is used to enable the contact wire under the structure to follow to some extent the movement of the contact wire in mid-span due to changes in temperature. The sectional area is reduced to $0\cdot6\,in^2$.

(*b*) Experimental use is being made of welded tubular anchor and supporting structures. After a satisfactory test showing that

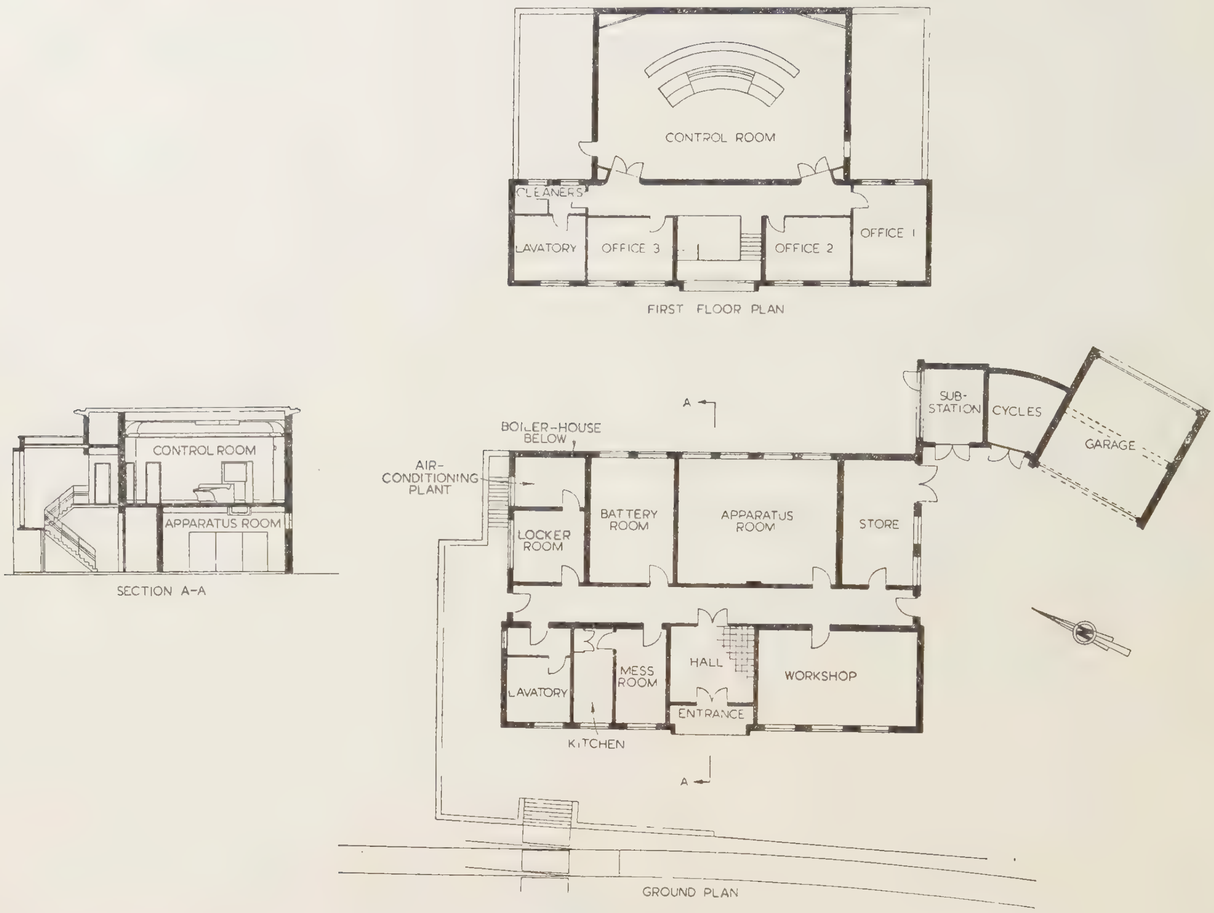


Fig. 5.—Plans and section of Penistone control station.

strength was maintained with a saving in weight of 40–50%, these were erected in Ashton Moss sidings. The time for painting and erection was considerably reduced.

(*c*) Several alternative designs of overlap spans are being tried: in one form the addition of a single intermediate supporting structure in mid-span and the introduction of a span length of contact wire spliced to the auxiliary catenaries of the adjacent span and suitable insulation at the splice and in the droppers would permit the introduction of overlap spans in long lengths of even 4 or 5 miles of track equipment without the use of anchor structures and splices in the contact wire.

(*d*) The insertion of spring-tensioned lengths of contact wire in place of the main and auxiliary catenary under low bridges has saved a vital 2 in of clearance and avoided in three cases the costly raising of overbridges which would have otherwise been necessary, track lowering being impossible in these cases.

(*e*) Numerous improvements have been made in detail designs of fitting, etc. Among these the trials of resin-bonded glass-fibre for registration arms and for the beams of section insulators probably signify further developments in the use of new materials, giving improved performance at places where high temperatures and pollution from steam locomotives is anticipated and further easement of the clearance difficulties by the use of materials providing high mechanical strength and insulating properties.

It was necessary to develop special forms of a number of constructions so that the contact-wire height could be maintained within due limits in spite of settlement caused by colliery subsidence. This type of construction was needed over 15% of the single-track mileage; its simplest form is illustrated in Fig. 6.

Fig. 7 illustrates the simple construction which was adopted in the new Woodhead tunnel, the supports being spaced 146 ft apart throughout.

(4.5.3) **Foundations.**

Foundations were constructed by the contractors for overhead-line equipment, and as a high proportion were in slatey rock, these proved to be an expensive item, accounting for approximately 12% of the total cost of the overhead equipment. They are either of the side-bearing or of the gravity type and were poured *in situ* after manual excavation.

(4.5.4) **Insulators.**

A much higher proportion of the insulators for registration arms are of the cap-and-pin type; otherwise the insulators follow very closely the designs used for the Shenfield electrification.

(4.6) Structure and Rail Bonding

The procedure also conforms to that for the Shenfield electrification, but replacement bonds are being reduced in section from 0·35 to 0·166 in^2, and single-rail bonding is being used in certain sidings.

(4.7) Lightning Arresters

Reliance is being placed on capacitors on the Wath Branch and parts of the main line, but on the later stages non-linear resistors are being installed on the track feeders.

(5) DESCRIPTION OF ROLLING STOCK

(5.1) $B_0 + B_0$ Locomotives

(5.1.1) **Mechanical Parts.**

The leading particulars of the $B_0 + B_0$ locomotives are given in Table 4. (See also Figs. 8 and 9.) The buffing and drawgears

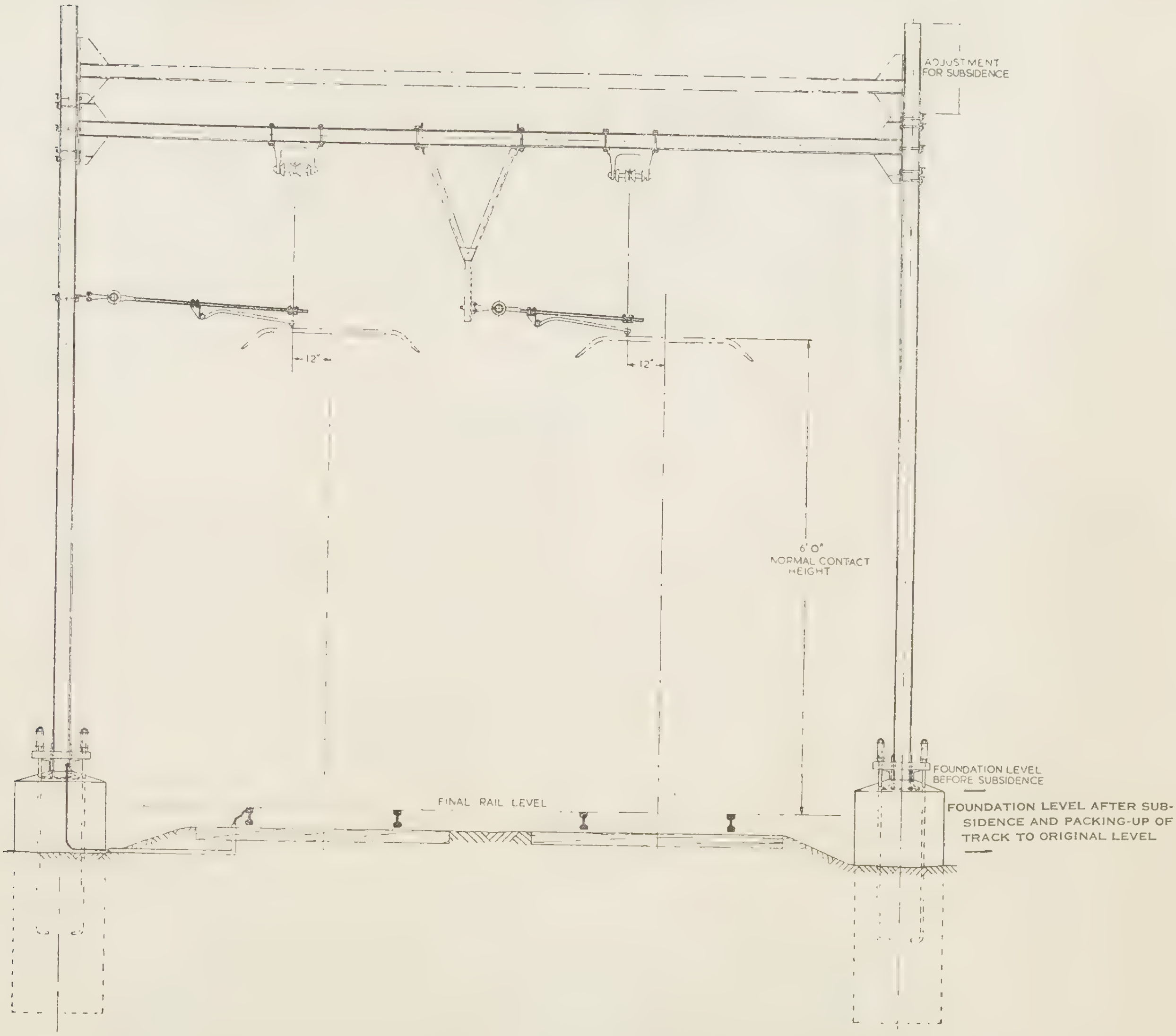


Fig. 6.—Two-track overhead-line equipment supporting structure: mining subsidence type.

are mounted on the bogie frames, and the two bogies are connected at their inner ends by an articulated coupling.

The bogies are built from 1 in steel plates secured together at the outer and inner ends by prefabricated dragboxes welded to the frames. The front dragbox, with the buffer beam as a base, carries buffers, drawgear, brake shaft and cylinder for the outer pair of wheels, while the inner dragbox is built as a continuation of the bogie frame, to which it is butt-welded and carries the brake shaft and cylinder for the inner wheels, together with the articulated joint by which means the bogies are coupled together.

At the centre of each unit a cast-steel stretcher is riveted to the frames and carries the motor nose-suspension brackets and the bogie centre slide and side control gear. The axle-boxes are guided by cast-steel horn blocks riveted to the frames and faced with manganese-steel liners welded to detachable steel shoes, and the suspension is provided by laminated springs mounted on top of the axle-boxes with helical auxiliary springs on the anchor bolts.

The body and understructure are spring-borne at four points on each bogie through semi-spherical bearing pads which rest on plungers carried in a guide secured to the outside of the bogie frames. The plungers in turn are supported by adjustable bolts

Table 4

LEADING PARTICULARS OF LOCOMOTIVES

Data	$B_0 + B_0$	$C_0–C_0$
Length over buffer	50 ft 4 in	59 ft 0 in
Wheel base	35 ft 0 in	46 ft 2 in
Wheel base of bogie	11 ft 6 in	15 ft 8 in
Distance between bogie centres	23 ft 6 in	30 ft 6 in
Overall width	9 ft 0 in	8 ft 10 in
Maximum height of body	13 ft 0 in	13 ft 0 in
Maximum height over raised pantographs	21 ft 0 in	21 ft 0 in
Weight in working order	86 tons 14 cwt	102 tons 10 cwt
Tractive effort—starting	45 000 lb	45 000 lb
Tractive effort—full-field continuous rating	14 600 lb at 32 m.p.h.	20 100 lb at 44 m.p.h.
Maximum speed	65 m.p.h.	90 m.p.h.
No. of motors	4	6
One-hour rating—full field	435 h.p.	450 h.p.
One-hour rating—weak field	467 h.p.	460 h.p.
Total locomotive 1 hour horsepower (weak field)	1 868	2 760
Motor ventilation	2 000 ft³/min	2 200 ft³/min

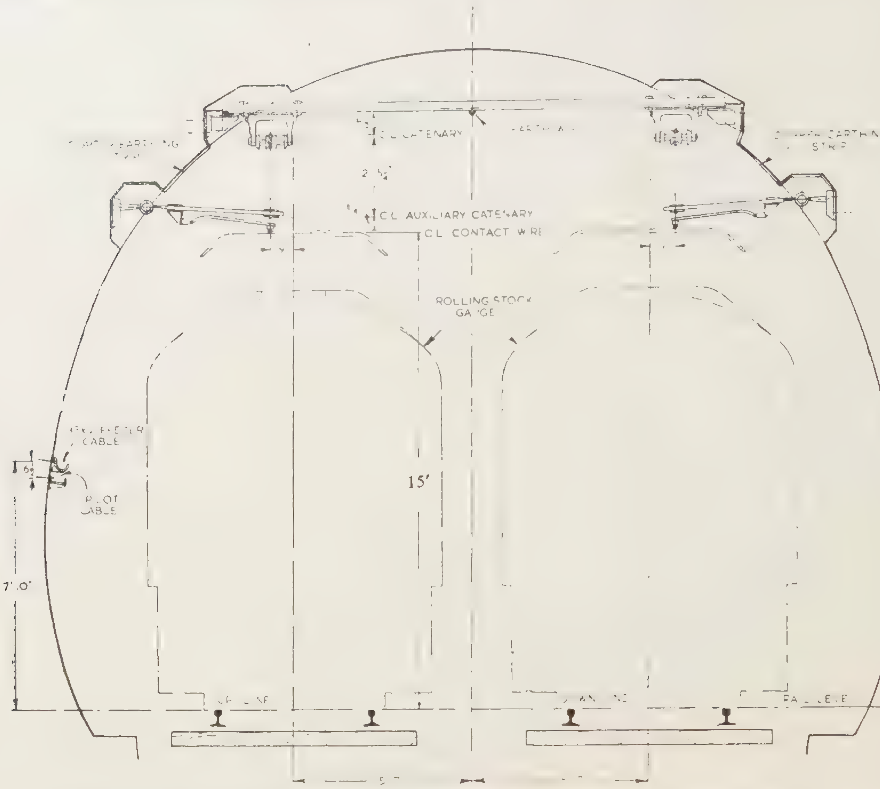


Fig. 7.—Overhead-line-equipment supporting structure—Woodhead tunnel.

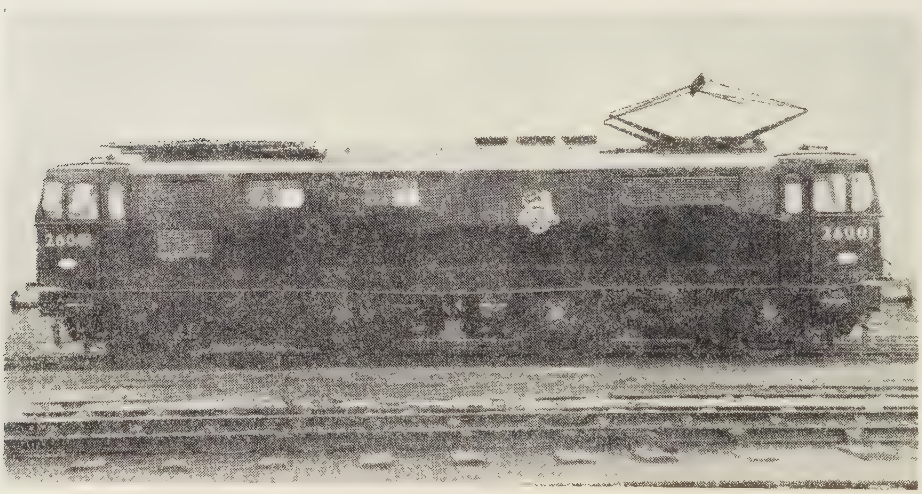


Fig. 8.—$B_0 + B_0$ mixed-traffic locomotive.

which engage the ends of a laminated spring pivoted in a bracket on the bogie frames between the plunger guides.

The understructure for the body is built up of $\frac{3}{4}$ in side-frame plates, and the bogie centre pivots are carried by a structure of flanged plates and channel sections riveted to the side frames. These pivots fit into spherical bushes housed in blocks which can slide transversely in the bogie-frame stretchers under the restraint of controlling springs. The block at No. 2 end bogie is free to move a small amount longitudinally to provide for the shortening of the centres on a curve. Thus a universal movement is obtained between the bogies and the understructure. The pivots have to transmit motion from the power bogies to the body structure, which carries all the machinery and controls and weighs 40 tons when completely equipped.

A footplate covers the whole floor, and on this a backbone of channel sections is mounted to carry the auxiliaries. Carlines riveted to the side frames support the curved sides and roof, the whole of which is detachable between the driving cabs. Identical cabs are provided at each end, and there is a side connecting corridor from which access is given to resistor, high-voltage and boiler compartments and other machinery.

As these locomotives are designed for mixed traffic in its widest sense, the brake equipment must be very flexible in its applications and consists of a straight air-brake and a vacuum-controlled Westinghouse air-brake operating clasp brakes with cast-iron shoes on each pair of wheels.

With passenger trains the locomotives must be able to haul standard British coaching stock—working from or to any part

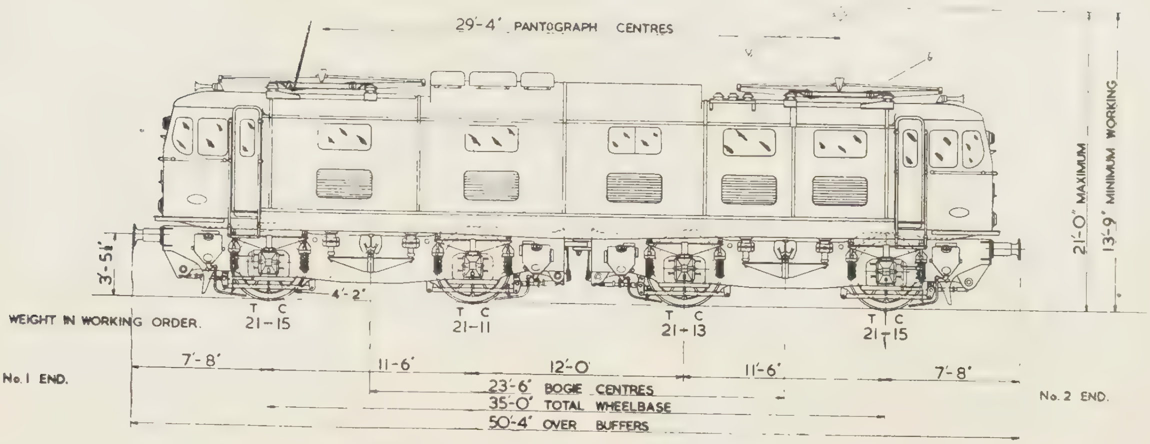


Fig. 9.—$B_0 + B_0$ mixed-traffic locomotive.

f the country—and must therefore be able, in winter months, o provide steam supply for coach warming, a service which is aken for granted with steam locomotives but is a snag with ll other forms of motive power. Fourteen of the $B_0 + B_0$ ocomotives are fitted with horizontal boilers of 4ft length and ft diameter, containing 180 tubes in which electric heating lements are located. The full loading is 360kW and the vaporation is 1 000lb at 70lb/in.[2]

The boiler is completely automatic in operation. A Mowbrey ontrol operated by water level opens or closes the by-pass alve from the electrically driven feed-pump, while a low-water evice and pressure-operated switches safeguard all working onditions.

.1.2) Electrical Equipment.

Each locomotive is equipped with four axle-hung nose-uspended series-wound motors, the two motors on each bogie eing permanently connected in series. Motor characteristic urves are given in Fig. 10. Each motor drives through a single-eduction gearing comprising a hardened, tempered and ground inion and a gear wheel with oil-hardened and tempered Maag volute teeth. The gear wheel incorporates either a rubber esilient connection between rim and centre, as shown in Fig. 11, r springs in the case of the 20 locomotives first built.

The driver, aided by ammeter, line and motor voltmeter and peed indicator, has complete control of each locomotive, utomatic speed control being impracticable owing to variation composition and type of train. Control can be effected from a aster controller at each end of the locomotive. There are ten onomical running speeds when motoring and taking current, mely full series, full parallel and four weak-field steps in ries and in parallel. The controller handle may be moved a resistance notch to lower the speed in both series and rallel motor connection. To assist in starting heavy trains running at low speed in adverse weather conditions, the st five steps of resistance of the 14 series steps may—when itially cold—be kept in circuit without undue heating for tween 5 and 10min. The motor fields are shunted to permit eakening of the field to obtain higher speeds and also to eaken the field of the leading motor of a pair to reduce its ctive effort and compensate for transfer of weight from front back axle and reduce tendency to front-wheel slip. The sistors are of cast iron, housed in a compartment, as shown Fig. 12, alongside another containing the high-voltage control ar. The doors of both compartments are interlocked with the ain isolating switch, so that before the door can be opened the ntographs must have been lowered and earthed.

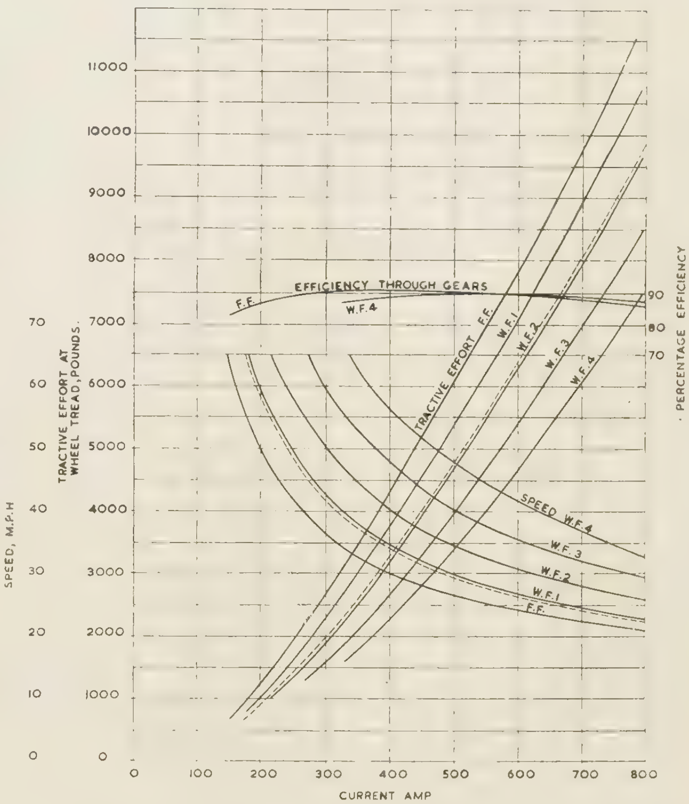


Fig. 10.—$B_0 + B_0$ locomotive—traction-motor characteristic.

Ratings		Output h.p.	amp	volts
One-hour	F.F.	435	510	700
	W.F.	467	540	700
Continuous	F.F.	310	360	700
	W.F.	340	397	700

Wheel diameter 50in
Gear ratio 17/70
Armature speed (r.p.m.) .. .. .. m.p.h. × 27·7

The main elements of the control circuit are shown schematically in Fig. 13.

Each locomotive has two motor-generator sets, one mounted at either end of the locomotive. Their series motors are fed

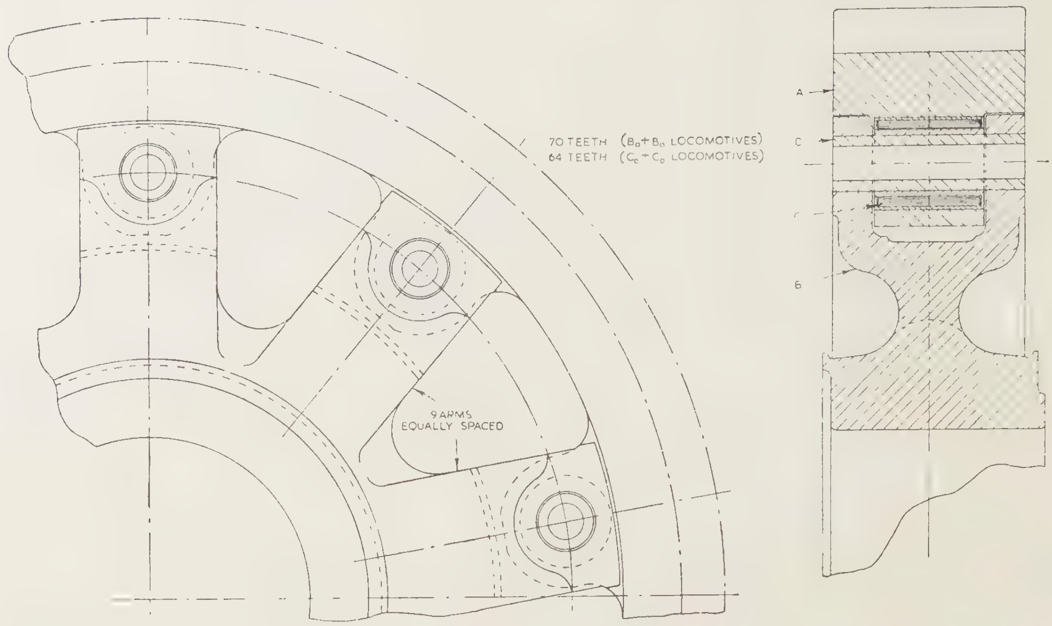


Fig. 11.—Resilient gear wheel.

A—Gear-wheel rim.
B—Gear-wheel centre.
C—Silentbloc bush.
D—Securing pin.

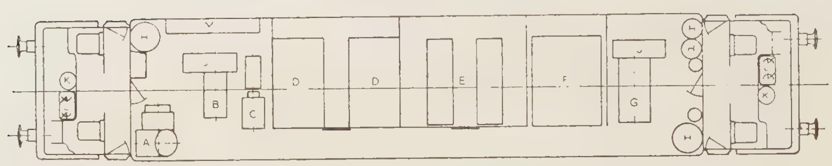


Fig. 12.—$B_0 + B_0$ locomotive—body layout of equipment.

A—Compressor.
B—Supply motor-generator.
C—Exhauster.
D—Resistors.
E—High-voltage compartment.
F—Boiler.
G—Exciter motor-generator.
H—Air reservoirs.
J—Traction-motor blowers.
K—Hand brake.
L—Master controller.
M—Battery.

through fuses and current-limiting resistors at line voltage. Control current is supplied at 50 volts by the supply motor-generator set in parallel with a 33-cell alkaline battery. The supply motor-generator is rated at 5kW and its voltage is automatically regulated to 50 volts to supply control, lighting and other auxiliary circuits; it also drives the blower supplying air to one pair of motors. The exciter motor-generator is rated at 35kW; it excites the main motor fields during regeneration, and drives the blower for the other pair of traction motors.

Regeneration, available both in series and parallel connection, is effective above about 16m.p.h. After adjusting the motor voltage to equal the line voltage, by manipulation of the "regeneration lever," the driver, on setting his controller to full series or full parallel, connects the motors to the line and can then vary the main motor excitation in 17 steps to produce the braking effort desired, provided that he does not exceed about 500amp or cause the line voltage to rise above about 1950 volts. If for any reason regenerative braking ceases, the air brake comes on automatically, and this also occurs if the driver fails to keep either the deadman's pedal or the hand button depressed for more than 6sec.

Each locomotive carries a 2-cylinder motor-driven geared compressor supplying air maintained at a pressure between 85 and 100lb/in^2 by an automatic governor, for locomotive brakes, control apparatus, pantograph, whistle, sanders and window wiper, and a 4-cylinder 2-speed direct-driven exhauste to operate the brakes of vacuum fitted trains. Both are drive by 1 500-volt series motors, protected by fuses and (except th exhauster) current-limiting resistors, and are mounted in one c the machinery compartments.

All four auxiliary machines, except the compressor, are sel ventilated, and they and the blowers draw air from the insid of the locomotive. Air filters are fitted.

Each locomotive is fitted with two pantographs, and both a normally in the up position when running. They are sprin controlled and air-operated, and arranged so that all circui except that for the compressor are opened before the pan leav the wire, whilst they are pulled down by their springs if a is released from their cylinders. They can also be raised by hand pump. The single pans are of galvanized steel with copp wearing strips and a light central auxiliary pan is fitted. Th other characteristics of the pantograph conform closely to thos described for the Shenfield electrification, except that the tot operating range is 8ft.

(5.2) C_0–C_0 Locomotives

(5.2.1) Mechanical Parts.

The leading particulars of the C_0–C_0 locomotives are liste in Table 4. (See also Figs. 14 and 15.) They differ basically fro the $B_0 + B_0$ locomotives in that they take buffing and tractio

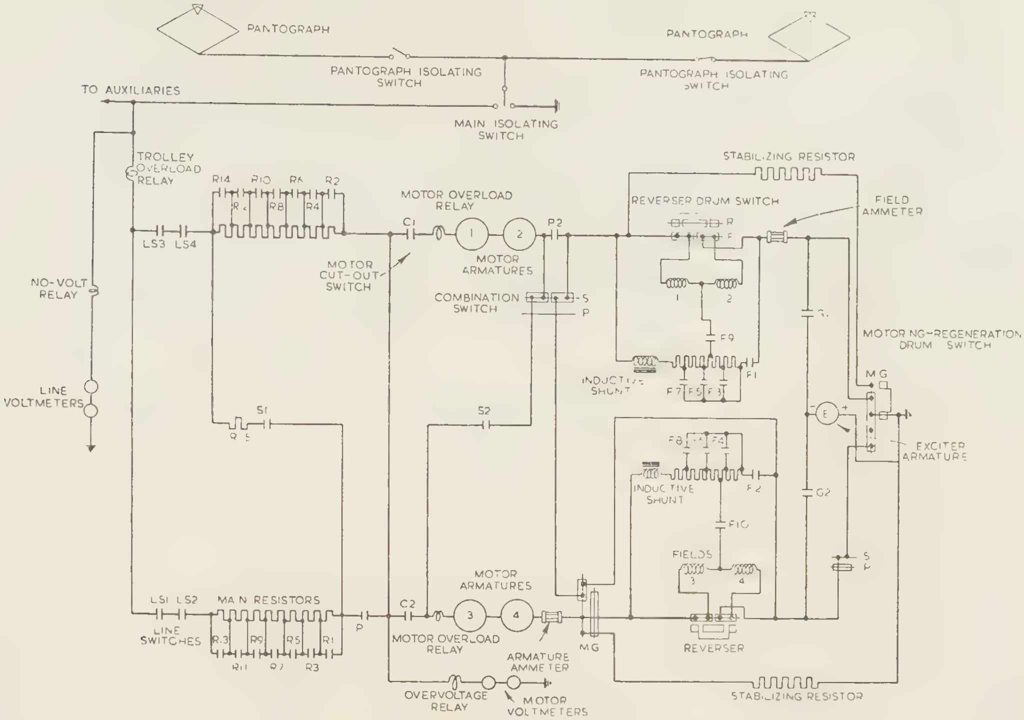


Fig. 13.—$B_0 + B_0$ locomotive—power schematic.

Fig. 14.—C_0–C_0 mixed-traffic locomotive.

rces through the under structure, leaving the two bogies inde-endent of each other, apart from their connections to the upper ructure frame. Whilst of the mixed traffic type, they are imarily intended for passenger working, and all are fitted ith electric boilers supplying steam for coach heating as already scribed.

The bogies are of the double-bolster equalized type with ames fabricated from 7/16in plates in box form so that the le-box guides are built in and the equalizing beams resting the axle-box top are accommodated inside the "box." wing to their length and complicated nature, the frames are ress relieved after fabrication. The two side units of each gie are braced together by cast-steel cross-stays in which the uble bolster can slide transversely, and through which the ctive force is transmitted via the bolster to the bogie centre on the body structure. Each of the three nose-suspended motors in one bogie is supported from one of the cross-stays by a link fitted with Silentblocs at each end and located laterally by a similar smaller link, so that the wheel bosses and motor-suspension bearings, which have a generous lateral clearance, never come into contact and all movement of the motor is accommodated by the Silentbloc.

The weight of the body is carried by four spherical bearers sliding on each bolster, which in turn rests on laminated springs supported by swing links from the bogie cross-stays. The equalizing beams are carried by twin coil-spring nests. Owing to the buffing and drawgear being fitted on the understructure, this is necessarily of more robust design than on the $B_0 + B_0$ type, and consists of rolled-steel sections suitably cross-braced and stiffened over the large-diameter bogie centres. The body

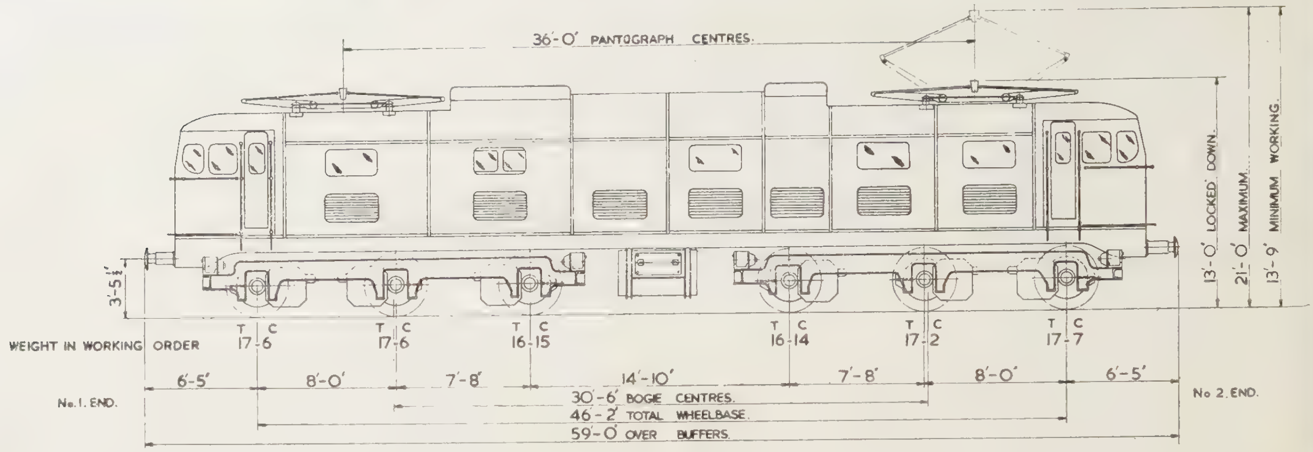


Fig. 15.—C_0–C_0 mixed-traffic locomotive.

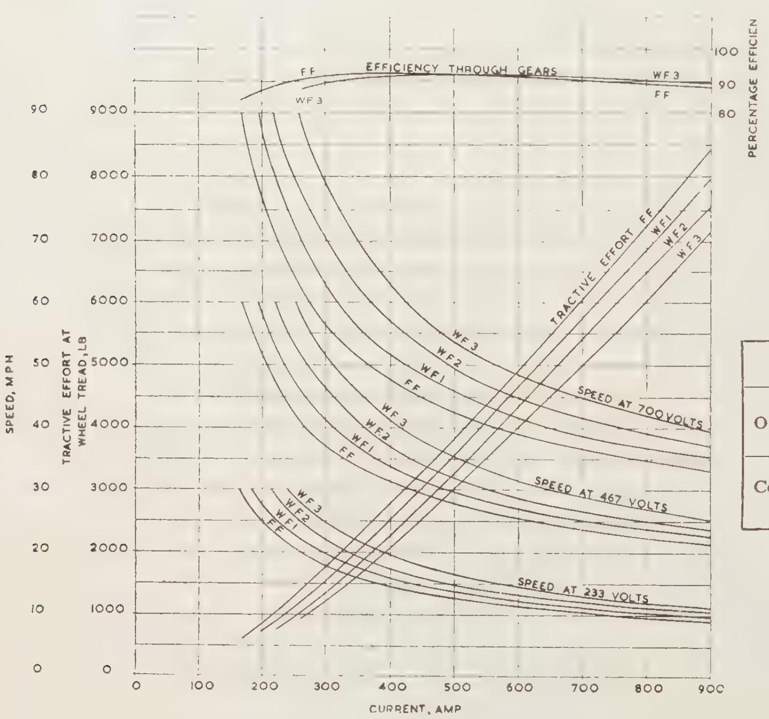


Fig. 16.—C_0–C_0 locomotive—traction-motor characteristics.

Ratings		Output h.p.	amp	volts
One-hour	F.F.	450	520	700
	W.F.	460	530	700
Continuous	F.F.	400	460	700
	W.F.	400	460	700

Wheel diameter .. .. 43in.
Gear ratio 17/64
Armature speed (r.p.m.) .. .. .. m.p.h. × 29·4

has a layout similar to that of the $B_0 + B_0$ type, except for an additional resistor chamber. The brake system is the same as on the other locomotives and operates the clasp brakes through four cylinders on each bogie and Westinghouse slack adjusters.

(5.2.2) Electrical Equipment.

The six axle-hung nose-suspended motors are arranged to give three fixed speeds. Motor characteristic curves are given in Fig. 16. To ensure good sharing of load between these locomotives in series and series-parallel connections and the $B_0 + B_0$ in series and in parallel connection, the characteristics have been arranged to match in preference to taking full advantage of the adhesion weight of the locomotive. In parallel connection the locomotive is capable of 90m.p.h., with new tyres, although this line does not permit full advantage being taken of the whole available speed range. There are twelve economical running speeds when motoring and taking current, namely series, series-parallel and parallel and three weak-field steps in each combination.

Otherwise the arrangement of motors and gears, of control gear, and equipment housing, conforms closely to that of th $B_0 + B_0$ locomotives.

The detailed design of the equipment reflects more recen practices, e.g. in the provision of silver butt interlock contac shielded against dust. Apart from the reverser, all 1 500 vo switching is carried out by unit switches; the master controlle have continuous movement covering all three speed combination

The arrangement of the equipment is shown in Fig. 17, an the main elements of the control circuit in Fig. 18.

The auxiliary equipment and facilities for regeneration con form generally to those of the $B_0 + B_0$, and wherever possib components serving the same purpose are identical.

(5.3) Multiple Unit Stock

The differences between the stock for this line and the Shenfiel line are, apart from the provision of first class accommodatio of a minor nature. There are contacts in the deadman's hand which cut power off immediately the handle is released, an single bifurcated jumpers between units which permit units t be coupled in any way.

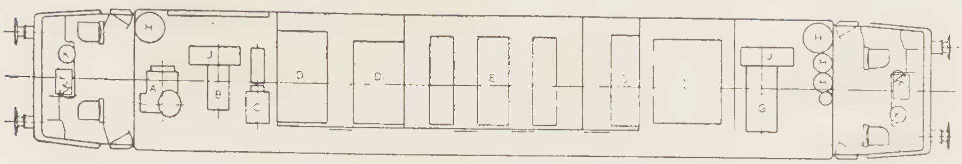


Fig. 17.—C_0–C_0 locomotive—body layout of equipment.

A—Compressor.
B—Supply motor-generator.
C—Exhauster.
D—Resistors.
E—High-voltage compartment.
F—Boiler.
G—Exciter motor-generator.
H—Air reservoirs.
J—Traction-motor blowers.
K—Handbrake.
L—Master controller.

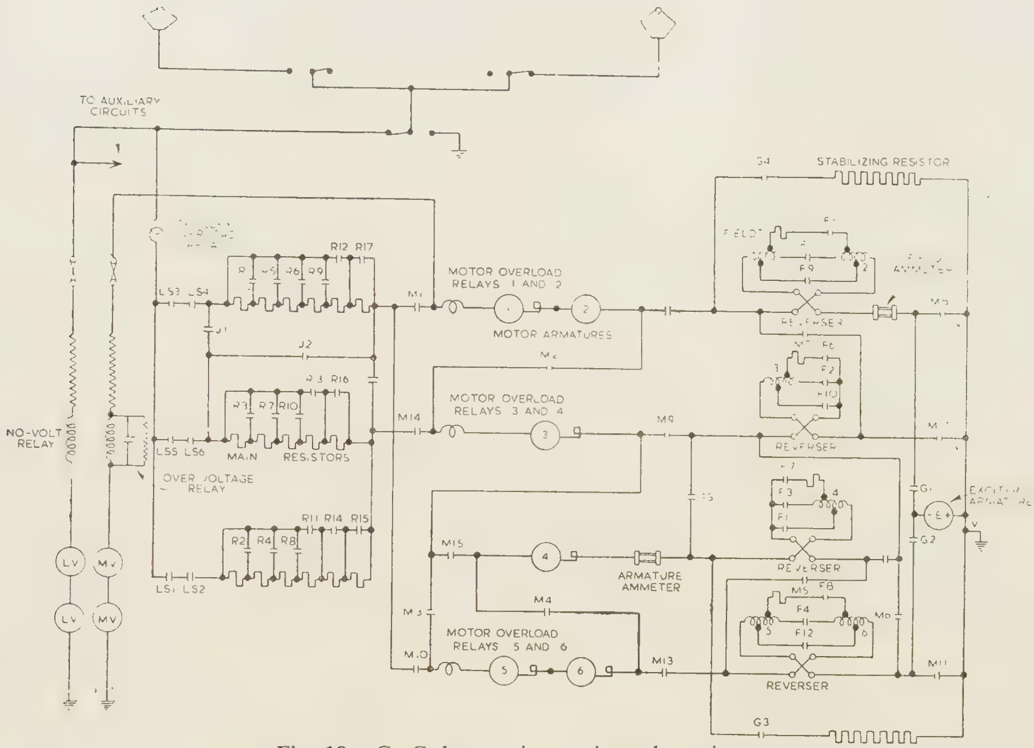


Fig. 18.—C_0–C_0 locomotive—power schematic.

LOCOMOTIVE AND ROLLING STOCK MAINTENANCE DEPOTS

Depots for the inspection and running maintenance have en provided at Reddish, Darnall and Wath (see Figs. 19, 20 d 21). Reddish depot also incorporates an overhead-line intenance depot: another has been provided at Penistone.

Reddish depot is double ended, although for this stage of velopment only one connection to the running lines is proed. It comprises inspection and light-repair bays, stores, rkshops, offices and amenities for staff. The building, 400 ft g, will accommodate 6-coach trains. The inspection bay has wired tracks provided with pits for half their length, and light-repair bay has one unwired track and a 35 ton overhead velling crane, and accommodates the overhead-line-equipment res and motor-transport garage. Dry carriage cleaning will carried out in the inspection bay; for wet cleaning an outr track with concrete apron and cleaning trollies has been vided. A sand-drying and supply plant is provided in the d; also water-filling points for the electric boilers on locoives. Storage sidings are provided for the eight 3-coach s and for overhead-line maintenance vehicles. Tungstennent lighting is used in the shed and yard, and in the pits.

Darnall is a much smaller depot, 150 ft long, with two wired tracks provided with pits throughout. No lifting facilities are available, and only inspections and emergency repairs will be made here. The shed is double-ended, and there are two connections to running lines. A sand-drying and supply plant and electric-boiler water-filling points are provided.

Wath depot is 200 ft long with two wired tracks provided with pits throughout, with hydraulic jacks for lifting bodies of locomotives, and a wall jib crane. The building was constructed on articulated principles to allow for mining subsidence. This has occurred, and the shed has suffered no damage. Wath will deal only with inspections on some locomotives and emergency repairs, but during the first two years of operation all maintenance work and lifting has been carried out at Wath.

(7) ERECTION AND SETTING TO WORK

The first $B_0 + B_0$ locomotive ran trials on the Manchester–Altrincham line in 1941, subsequently running some 330 000 miles in service on the Netherlands Railways. The mechanical parts of the remaining 57 $B_0 + B_0$ and 7 C_0–C_0 locomotives were built at Gorton, and the electrical equipment was erected at Dukinfield between 1949 and 1954. The first electric locomotive ran on the Manchester–Sheffield–Wath line at Wath on the 3rd June, 1951.

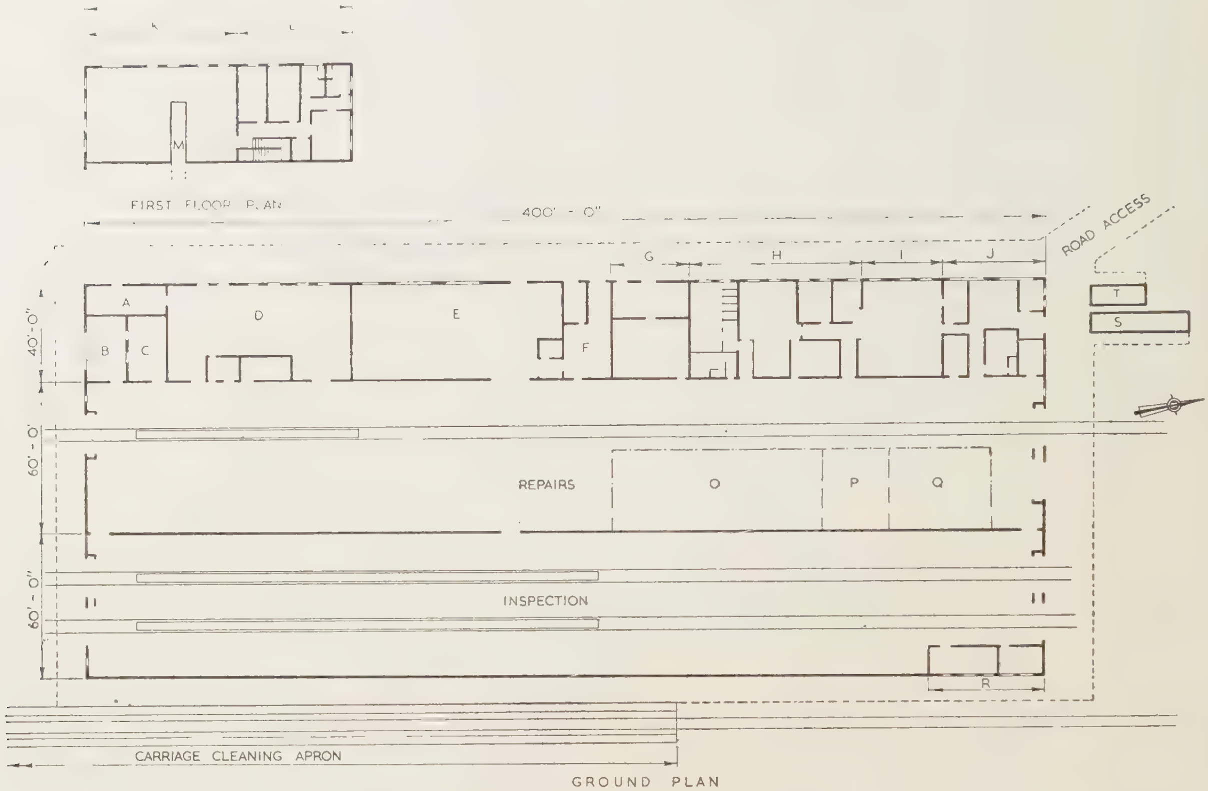


Fig. 19.—Reddish inspection and light-repair shed.

A—Substation.
B—Battery room.
C—Compressor room.
D—Brake fitter's shop.
E—General store.
F—Oil store.
G—Fuel store and boiler house.
H—Staff amenities.
I—Mess room.
J—Entrance and offices.
K—Pantograph shop.
L—Offices.
M—Pantograph retractable table.
O—Cable and overhead-line-equipment store.
P—Overhead-line-equipment workshop.
Q—Garage.
R—Operating department accommodation.
S—Cycle shed.
T—Motor-cycle shed.

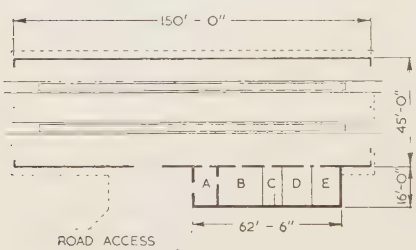


Fig. 20.—Darnall inspection shed.

A—Oil store.
B—General store.
C—Lavatory.
D—Mess room.
E—Office.

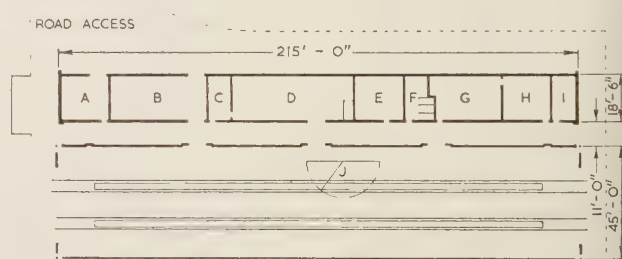


Fig. 21.—Wath inspection shed.

A—Oil store.
B—General store.
C—Substation.
D—Workshop and shop office.
E—Shed-staff locker and mess room.
F—Lavatory.
G—Motormen's locker and mess room.
H—Office.
I—Time lobby.
J—Jib crane.

Training of drivers has proceeded almost without an interval from 1951 to the present time.

Aldam Junction substation and Penistone control station were commissioned in April, 1951.

The 33kV transmission cables and pilot cables were laid and commissioned concurrently between 1950 and 1954.

(8) EXPERIENCE ON WATH BRANCH

(8.1) General

The short length of 18 miles which has provided the first piece of concentrated freight haulage by electric traction in the British Isles is literally crowded with testing points, and it may safely be said that physical and technical difficulties are likely to b much less in practically all other parts of the country.

On one occasion a particularly violent thunderstorm cause more than forty lightning strikes on the electricity supply ne work and affected three locomotives in service. Trouble fro icing of conductors has been negligible, and generally any inte ruptions due to wintry conditions have been caused by snow i the points.

(8.2) Fixed Equipment

Adjustment of 5ft has been allowed in the design of contact-ne supports in areas liable to subsidence, and at one location nis has been completely absorbed. Further provision in such ases entails building up of foundations and lifting the sup-orting structures to a height which will enable the girder to evert to a lower position on the uprights.

The supervisory control over the system from Penistone ontrol has functioned satisfactorily, and the few cases of ailure have been due to dust on contacts in substations. In o case has any interruption of supply resulted. Two failures f rectifiers due to leakage through the anode ignition seals ave been dealt with by redesigning the seals. Some trouble as been met in the cable joints owing to mechanical stress aused by movement of the cables. Examination of joints by -rays has been extensively used in investigating the causes; this an entirely new technique and seems to have great potentiality or revealing the condition of parts hidden from the human eye fter the work has been completed.

(8.3) Rolling Stock

The heavy mineral and freight trains are composed mainly of oose-coupled unbraked stock, and drawgear limitations and ther circumstances necessitate one locomotive on double-ngine loads being at the rear. Under the worst conditions, dhesion has been found to be as low as $0{\cdot}17$. The assisting ngine at the rear is the more likely to slip, and as it does so, verload is thrown on to the train engine.

One cause arises from wet small coal, drippings from which ll on to the track, making the conditions worse for the rear ngine. A large quantity of this traffic is carried over the line, nd such wagons are the most heavily loaded.

This slipping, and also the difficulty of synchronizing the ovement from series to parallel working between the two loco-otives, has thrown considerable strain on the bogie centre ivots. Probably the effects of inertia from the bodies of the $_0 + B_0$ locomotives were underestimated, and it has been found esirable to replace the original cast-steel pivots by forgings, educing the leverage by shortening the pivot and interposing a n plate between it and the understructure of the body.

Initially, the extremely dirty condition of the atmosphere used difficulties with air filtration. The contamination arises om three main sources, namely the sooty and smoke-laden mosphere, cast-iron dust from brake shoes and the exhaust om the traction-motor blowers stirring up carbonaceous posit—which has accumulated over the years from the cause entioned above—on the track. The filters in the body sides pidly—i.e. in the course of a few days—became partially ogged, and the air found its way through all possible inlets d crevices, partly through the driving cabs, making them cold d draughty. Negative pressure in the high-voltage and resistor mpartments led to deposition of dust, some of it metallic, in em, and extensive work of blowing out and cleaning was cessary. The solution has been to reduce the degree of ration and to divert from the blowers a direct air-stream into e high-voltage compartment in order to put this at a pressure ghtly above atmosphere and thereby restrict the ingress of ally unfiltered air.

Standard working arrangements utilize both pantographs— reduce the collection per pantograph. This has been beneficial many cases where it is not possible to adjust for subsidence y by day, in sidings not frequently used, where contact wires come contaminated with smoke and particularly for supplying full-steam heating load when locomotives are stationary. th lac and grease have been used for pantograph contact-wire lubrication, and after much experiment it has been decided to adopt an appropriate grease.

Tyre wear is naturally heavy on this section of the line, and tyres have required re-turning at 35 000–40 000 miles. Work of this kind is carried out at Gorton Locomotive Works, as also will be casual repairs of an extensive nature and all long-period overhauls. Day-to-day servicing is catered for on a systematic basis at the Electric Depots on time periods of 5, 30 and 60 days. The short-period servicing requires 2 hours, and is carried out between turns on a round-the-clock basis. The 30- or 60-day servicing requiring 8 hours is completed in the normal day shift, and the locomotive is available for a turn commencing after 5p.m. Availability has been of the order of 96%. It has not been possible yet to obtain firm figures of availability, including works overhauls, since the tyre turning has so far been arranged in conjunction with modifications, referred to earlier, but with interchange of bogies, etc., it is anticipated that a high availability will be maintained.

(8.4) Operation

The heavy traffic on the initial stage of electrification has been very satisfactorily handled and the encroachment into the week-end to clear each week's loadings has been greatly reduced.

Nevertheless the full traffic potentialities cannot be realized while steam-hauled freight trains from Sheffield and Barnsley are sandwiched between electric trains so that the average speed tends to be reduced to that of steam operation. This position was somewhat eased by the opening of the new tunnel and by the introduction of full electrified operation from Manchester as far as Penistone, but it awaits the final extension to Rother-wood Exchange sidings, east of Sheffield, in order to realize the full traffic possibilities.

(9) POSSIBLE FUTURE EXTENSIONS

The present scheme is of too isolated a nature to permit the full benefits of electrification being achieved. In particular, it is not large enough to allow the closing of any motive-power depot and most trains suffer a change of motive power from steam to electric at Rotherwood or Wath, and vice versa in the Manchester yards. Investigation is now being made of the most efficient way of extending the electrification. The cost of electrifying the lines from the collieries and marshalling yards south of the present termination at Rotherwood seems likely to be appreciably less proportionately than that of the work com-pleted. These lines are relatively simple in pattern and would permit the use of newer less-costly techniques developed since the present scheme was planned.

Development of this area would naturally lead to considera-tion of extending the electrification eastwards to Lincoln and Whitemoor and southwards down the old Great Central line, by which freight traffic could pass expeditiously to the Western Region via Woodford and Banbury.

On the western side, the flow of traffic is much more diverse, and it would seem that the most likely immediate development is of a suburban character based on completing the present electrification to Manchester Central and electrifying the lines to Hayfield and Rosehill.

(10) FUTURE DESIGN TRENDS

As nearly 20 years have elapsed between the inception of this scheme and its completion, it is not surprising that new know-ledge has become available and that fashion has changed so that differences in equipment will be considerable if these exten-sions proceed. Some indication of these follow for each main section.

Power Supply.—So far as possible, the tendency would be to take local supplies at the substations and thus avoid costly railway-owned h.v. feeders. If possible, supplies would be taken at 11 kV.

H.V. Cables.—If 33 kV cables were essential, e.g. in areas such as the actual Pennine crossing, where no other use for electricity exists, they would be of the oil-filled type, suitably served with p.v.c. or other non-permeable servings, buried direct if the terrain allowed or continuously supported in concrete troughs or asbestos cement pipes.

H.V. Switchgear.—This would be of the indoor metalclad, compound-filled type, with minimum oil circuit-breakers.

Rectifiers.—These would be of the pumpless fan-cooled type in glass or steel containers, unless other types superseded the current mercury-arc rectifier.

D.C. Switchgear.—This would be truck-mounted and probably solenoid-operated from a power battery.

Supervisory Control.—This would probably be of a type giving direct control and indication of each switch from a miniature diagram.

Overhead-Line Equipment.—If, as seems probable, present substation and track-paralleling hut spacings were maintained, the cross-section of overhead conductors would be reduced and advantage taken of increased knowledge and experience to increase span lengths and reduce weight of structures. Single cap-and-pin insulators would be used with non-ferrous fittings and registration from span wires. Wherever possible foundations would be mechanically excavated, using a truck-mounted power auger to produce small deep cylindrical foundations.

Locomotives.—New designs are in preparation for standard locomotives, probably including central cab, with multiple-unit control, air-blown resistors with vernier notching and the maximum use of vertical-shaft rotary drives for auxiliaries so as to economize floor space. It seems probable that $B_0 - B_0$ and C_0–C_0 locomotives will satisfy all except a few classes of train and may be arranged with double reduction gears to reduce motor weight. Passenger trains will increasingly be of the high-speed light-weight multiple-unit type, allowing the full benefits of electrification to be available to passengers and to railway operating and motive power staff, and allowing locomotives to be designed for the freight services for which they are most suitable, without the complications introduced by attempting to make a mixed-traffic type, e.g. boilers would be unnecessary. It is probable that increased attention will be paid to camshaft-type controllers to economize space. In general the object will be to reap the benefits of improved manufacturing techniques, which should allow of practically unlimited life on the track without servicing.

(11) ACKNOWLEDGMENTS

The authors wish to thank the British Transport Commission for permission to publish the paper. They wish also to thank their colleagues and the contractors for their skill and forbearance throughout the progress of the work, and members of their staff for their great part in it and for assistance in the preparation of the paper.

They also wish to place on record the parts played by the late Sir Nigel Gresley, Mr. H. W. H. Richards and Mr. H. H. Swift in the inception, planning and initial stages of the work.

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(13) APPENDICES

(13.1) Substation Equipment

(13.1.1) Oil Circuit-Breakers.

Symmetrical breaking capacity	500 and 750 MVA
Type of arc-control device	Turbulator
Weight of 3-phase oil circuit-breaker (complete with oil)*	5 600 lb
Quantity of oil	135 gal
Opening time	3·25 cycles
Making time	5·5 cycles
Make-break time from operation of relay	7·5 cycles
Arcing time:	
(*a*) at rated breaking-capacity current	1·15 cycles
(*b*) at 60% rated breaking-capacity current	1·4 cycles
(*c*) at 10% rated breaking-capacity current	2·0 cycles
Total break time	4·4 cycles

(13.1.2) Power-Operated Isolators.

(*a*) Motor operated off-load rotary type	
(*b*) Continuous current rating	400 amp
(*c*) Short-time rating up to 5 sec	13 150 amp
(*d*) Operating motor voltage	50 volts
(*e*) Operating time	9 sec
(*f*) Total weight (excluding mechanism)	1 680 lb
(*g*) Weight of mechanism and housing	672 lb

(13.1.3) Rectifier Transformers.

Primary connection	Delta
Number of secondary phases	12
Efficiency at 0·25 × full load	98·03%
Efficiency at 0·5 × full load	98·41%
Efficiency at 1 × full load	98·03%
Efficiency at 1·5 × full load	97·39%
Efficiency at 2·0 × full load	96·61%
Efficiency at 3·0 × full load	94·98%
Impedance voltage	9·5%
Quantity of oil	1 700 gal
Total weight of transformer	49 400 lb
Normal capacity	3 245 kVA

(13.1.4) Mercury-Arc Rectifiers.

	Water cooled	Air cooled
Nominal capacity	2 500 kW	2 500 kW
Number of cylinders per complete rectifier unit	1	2
Weight of each cylinder with auxiliaries	†11 468 lb	5 824 lb
Efficiency at 0·25 × full load at 50°C	98·35%	97·03%
Efficiency at 0·5 × full load at 50°C	98·44%	97·72%
Efficiency at 1·0 × full load at 50°C	98·18%	97·90%
Efficiency at 1·5 × full load at 50°C	98·0%	97·93%
Efficiency at 2·0 × full load at 50°C	97·74%	97·89%
Efficiency at 3·0 × full load at 50°C	97·20%	97·78%
Combined efficiency of rectifier and transformer:		
(*a*) At 0·25 × full load	96·41%	95·12%
(*b*) At 0·5 × full load	96·87%	96·18%
(*c*) At 1·0 × full load	96·24%	95·98%
(*d*) At 1·5 × full load	95·44%	95·38%
(*e*) At 2·0 × full load	94·42%	94·57%
(*f*) At 3·0 × full load	92·32%	92·87%

Power factor at normal voltage:

	Water cooled	Air cooled
(*a*) At no load	0·22	0·22
(*b*) At 0·25 × full load	0·945	0·945
(*c*) At 0·5 × full load	0·960	0·960
(*d*) At 1·0 × full load	0·959	0·959
(*e*) At 1·5 × full load	0·947	0·947
(*f*) At 2·0 × full load	0·906	0·906
(*g*) At 3·0 × full load	0·887	0·887

* 6 000 lb for 750 MVA at Gorton substation.
† Excluding main re-cooler unit: weight 2 352 lb.

(13.1.5) **High-Speed Circuit-Breakers.**

	Rectifier	Feeder
Continuous-current capacity	2 000 amp	1 600 amp
Minimum operating voltage	1 150 volts	1 000 volts
Time for rupturing dead short-circuit (i.e. no external inductance)	0·022 sec	0·022 sec
Range of overload settings	2 500 amp	3 000–5 000 amp
Weight of circuit-breakers	530 lb	480 lb
Current rating of isolators	2 000 amp	1 600 amp

(13.2) Rolling Stock

(13.2.1) **Locomotives.**

	$B_0 + B_0$	$C_0–C_0$
Number of units	58	7
Tare weights:		
Mechanical	52·9 tons	66·5 tons
Electrical	33·1 tons	35·5 tons
Total	86·0 tons	102 tons
Total in working order	86·7 tons	102·75 tons
Length over buffers	50 ft 4 in	59 ft
Width of body	9 ft	8 ft 10 in
Height with pantograph lowered	13 ft 1 in	13 ft 1 in
Maximum service speed	65 m.p.h.	90 m.p.h.
Wheel diameter	50 in	43 in
Number of motors	4	6
Continuous rating—full field	1 240 h.p., 31·9 m.p.h.	2 400 h.p., 44·2 m.p.h.
Continuous rating—weak field	1 360 h.p., 51·5 m.p.h.	2 400 h.p., 57·5 m.p.h.
One-hour rating—full field	1 740 h.p., 26·3 m.p.h.	2 700 h.p., 41·5 m.p.h.
One-hour rating—weak field	1 868 h.p., 45·3 m.p.h.	2 760 h.p., 52·7 m.p.h.
Maximum tractive effort	45 000 lb	45 000 lb
Type of gears	Single straight spur, resilient	
Gear ratio	17/70	17/64
Minimum clearance to rail	4½ in with fully worn tyres	
Weight of motor with gears and gear case	10 642 lb	7 112 lb
Ventilating air per motor	2 000 ft³/min	2 200 ft³/min
Type of control	Hand-notched electro-pneumatic contactors. Drum switches for motor grouping	Hand-notched electro-pneumatic contactors
Number of notches:		
Series	15	17
Series parallel	—	10
Parallel	14	8
Weak field	4 in each combination	3 in each combination
Low-voltage supply	50 volts for control, lights and cab heating	
Heating	3 kW per cab	
Number of locomotives fitted with boilers	14	7
Boiler rating	360 kW	
Boiler output	1 000 lb/h	
Continuous rating of supply motor-generator set	5 kW, 1 450 r.p.m.	
Continuous rating of exciter motor-generator set	36·5 volts, 685 amp, 1 130 r.p.m.	
One-hour rating of exciter motor-generator set	45 volts, 780 amp, 1 020 r.p.m.	
Continuous rating of compressor	Approximately 9 h.p., 1 400 volts, 100 lb/in²	
Compressor displacement	38 ft³/min at 1 200 r.p.m.	
Rating of exhauster	Approximately 7½ h.p. high speed, 3½ h.p. low speed	
Exhauster displacement	132 ft³/min at 1 200 r.p.m. 82·5 ft³/min at 750 r.p.m.	
Battery	Cadmium-nickel-iron alkaline 40 Ah at 5 h rate, 33 cells	
Brakes	Westinghouse vacuum-controlled straight air-brake with automatic emergency and regenerative failure features.	

(13.3) Multiple-Unit Stock

	Electrical tons	Mechanical tons	Total tons
Number of units			8
Tare weights:			
Motor coach	16·975	35·09	52·065
Trailer coach	0·685	25·72	26·405
Driving trailer-coach	0·800	26·68	27·480
Three-coach unit	18·460	87·49	105·950

Length over buffers:	
Three-coach unit	177 ft 7 in
Six-coach train	355 ft ½ in
Width of coach body	9 ft 3 in
Height with pantograph lowered	13 ft 1 in
Number of seats (six-coach train)	352 persons
Standing room (six-coach train)	440 persons (estimated at 2 ft² per person)
Maximum service speed	70 m.p.h.
Balancing speed on level track	64 m.p.h. with 175% seated load
Wheel diameter	43 in
Average acceleration	1·25 m.p.h./sec to 22·5 m.p.h.
Average retardation	2·0 m.p.h./sec from 30 m.p.h.
Continuous rating of unit	628 h.p., weak field, 1 400 volts
One-hour rating of unit	840 h.p., weak field, 1 400 volts
Horse-power per ton, all seats occupied	7·2, weak field, one hour rating
Average accelerating current per unit	628 amp with motors in parallel
Type of gears	Single straight spur, case-hardened
Gear ratio	18/69
Minimum clearance to rail	4½ in with fully-worn tyres
Weight of motor with gears and gear-case	6 123 lb
Type of control	Multiple-unit with automatic acceleration, electro-pneumatic contactors
Number of notches	Shunting—1 Series—9 Parallel—5 Weak field—1 (in parallel)
Low-voltage supply	52 volts for control, lights, brake and door circuits
Heating	Approximately 8 kW per coach—sets of seven 400-watt heaters in series across 1 500 volts
Continuous rating of motor-generator set	6 kW
Continuous rating of compressor	Approximately 8 h.p. at 1 400 volts, 100 lb/in²
Displacement of compressor	38 ft³/min at 1 200 r.p.m.
Battery	Cadmium-nickel-iron-alkaline, 125 Ah at 5 h rate, 33 cells
Brakes	Westinghouse electro-pneumatic with self-lapping drivers' brake valve
Doors	Peters's electro-pneumatic with individual coach isolation.

(13.4) Overhead Equipment

Length of route equipped	68 miles
Length of single track (running lines)	212 miles
Length of single track (sidings)	88 miles
Construction of equipment	Similar to overhead equipment of Liverpool St.–Shenfield line except that the minimum height of the contact-wire on the Manchester – Sheffield – Wath line is 13ft. 9in.

[The discussion on the above paper will be found overleaf.]

DISCUSSION BEFORE THE INSTITUTION, 2ND DECEMBER, 1954

Mr. C. K. Bird: In spite of the time that has passed since the inception of this scheme, it is gratifying to see that there has been comparatively little change in the tonnage conditions with which this electrification was planned to deal. Although there has been a slight shift in the production of coal to the Nottinghamshire coalfield in place of the Yorkshire one, the problem of traffic is still the same—that of very heavy mineral traffic, mainly passing east to west. To that extent, the success or failure of this electrification scheme provides a fair test as to the efficiency with which the plans were carried out and the efficiency of all the planning that has gone into it.

I should therefore like to take this early opportunity of reviewing in some little way the results which have so far been achieved.

The authors have already mentioned that a speed limit of 65m.p.h. is imposed for track reasons, so the full capacity and capabilities of the C_0–C_0 locomotive cannot be developed. None the less, in contradistinction to the adverse comment made by Mr. Allen in the current *Railway Magazine* on the deterioration of times from Sheffield to Manchester, where he quotes a very good run by a B.17 steam locomotive with a seven-coach train as running from Sheffield to Penistone in 19min, the C_0–C_0 locomotives have achieved that in just under 15min with nine coaches.

I should next like to comment on the excellent way in which the motor-men have taken up their training and the skill that they have already developed to quite a high degree. A number of these men are advancing in years, and that makes their speed in picking up this new technique particularly gratifying.

Further on the question of speeds, on the freight side, the freight-train group return for the appropriate section shows in 1953 for a particular four-week period in September an average speed of 8·4m.p.h. For the corresponding four weeks this year the average is 10·5m.p.h., which is an increase of 25%.

Typical speeds included in that are Wath to Mottram, steam time 5h 5min. With stage one of the electrification there is a change-over from electric to steam at Barnsley Junction. The time is 3h 4min. At stage two, which was brought into operation in July, the time is 2h 20min. Included in that, of course, is the famous or infamous Woodhead tunnel, where the average time taken to run through the tunnel under steam conditions on 2nd June was 11·2min, and that has been reduced successively to 6·7 and 5·8min.

The improvements which have been made on the passenger side are, one is glad to see, meeting with the approval of the public. From Manchester to Sheffield during the period 20th September to 30th October, the increase in passengers has been 37%, while in a portion of the multiple-unit service there has already been an increase in both passengers and receipts of over 125%.

I should like to comment on the Section of the paper entitled "Co-ordination of Work." The authors stress the necessity of working together, department by department. I cannot emphasize that too much, because if we are going to proceed quite shortly into an era of major capital development, one of the things we must think out is how we are going to organize for it. We must not allow our provision of equipment to run ahead of our efficiency in bringing it into operation, or, afterwards, of our efficiency in using it.

Mr. C. M. Cock: The electrification of the Manchester–Sheffield–Wath lines was authorized by the former Board of the London and North Eastern Railway Company in 1936, and was completed this year.

After making allowance for the six years of war, when little or no construction was carried out, and another two years for the transition from war to peace, it has taken ten years to complete 75 route miles. That is an annual rate of construction of 7·5 route miles. During the four years preceding the 1939–45 War, the former Southern Railway Company were bringing electrification into use at an average rate of 90 route miles per year and probably they could have stepped up the rate of construction.

General electrification in this country is long overdue, but at last there are indications of a will to proceed.

But according to a recent Press report, there seems to be an impression at the British Transport Commission that delivery of equipment by British industry is an uncertain factor in a plan for reconstruction which one must presume contains a large element of main-line electrification. The capacity of technical staff is said to be another uncertain factor. Is it the intention to electrify at the rate of 7·5 route miles per annum or 90 route miles per annum, or something quite different?

Any doubt should be cleared at once with regard to the ability of British industry to undertake large-scale electrification in Britain. Experience has been obtained all over the world under widely diverse climatic, technical and operating conditions. Manufacturing capacity is already ample, and it can, if necessary, be expanded to meet any reasonable acceleration in any electrification programme that may arise.

It is not clear what is meant by the capacity of technical staff. It may well be that the staff of British Railways is inadequate—numerically, I mean. But it must not be forgotten that there are available in this country other organizations employing men of vast experience and knowledge of railway electrification, both at home and abroad. These could be enlisted, if necessary. If the Southern Railway Company could electrify 90 route miles per annum before the war, I suggest that by suitable and energetic organization, it would be possible to carry out electrification in independent groups totalling, say, on a conservative basis, 300 route miles per annum. But this is not enough, for at this rate a generation would pass before even one-third of the route miles of this country were electrified, and I suggest that some serious thinking is necessary on this point.

With regard to the $B_0 + B_0$ locomotives on the Manchester–Sheffield–Wath electrification, I should like to hear something further from the authors on the mechanical performance. I believe a locomotive with articulated bogies is never a good riding locomotive, and it is detrimental to the track.

Regenerative braking is said to be effective above about 16m.p.h. It is not mentioned in the paper, but Mr. Cook said this evening that there is some doubt about this range being suitable. On one railway with which I have been associated, 1 500-ton trains are worked on descending gradients of 1 in 37 at a maximum speed of 10m.p.h. for safety reasons, but the regenerative braking is effective down to about 7m.p.h.

The trains referred to are tight-coupled and continuously braked. The handling of loose-coupled unbraked trains, such as are worked on the Manchester–Sheffield electrification, is much more difficult and would seem to call for regenerative braking down to a speed very much lower than 16m.p.h.

I am surprised that grease is used for the lubrication of pantographs. Elsewhere a hard lacquer-bound graphite compound has been found to give a life to the pantograph wearing strips of about 40 000 miles compared with 14 000 miles for the grease-lubricated strips. But some perseverance is necessary to get the right mixture of the compound, and perhaps the services of the research department are necessary.

With regard to future trends, I should like to caution the

authors on their suggestion to increase the span length of the overhead equipment. No details are given in the paper of existing span lengths, but I assume that, since this electrification is similar to the Liverpool-Street–Shenfield electrification, these are a maximum of 210 ft. Spans of 300 ft were adopted on the Melbourne electrification about 40 years ago, and on many occasions during gales the contact wire was blown off the pantograph with disastrous results, and expensive modifications were necessary to prevent this.

A train-heating boiler, both in an electric and a Diesel-electric locomotive is offensive. Nobody in this country has yet produced anything really reliable for the latter. It is to be deplored, however, that this should be a reason against the very convenient mixed-traffic locomotive. The boiler properly belongs to a special tender, and the electrical engineer should not consider it retrograde or undignified to attach one of these things to an electric locomotive, in accordance with the ancient tradition of steam, for the winter season only. Incidentally, is 1 000 lb of steam per hour sufficient to warm a British train? It is suggested that double this quantity is necessary to avoid complaints from the patrons of British Railways. Electric heating of carriages is, of course, the best solution with electric traction.

Mr. O. J. Crompton: The spacing between droppers on the contact-wire is just the same on the simple as on the compound catenary. The stitched wire, or Y-construction, as it is known on the Continent, is superimposed on simple catenary construction to enable the contact wire under the structure to follow to some extent the movement of the contact wire in mid-span owing to the change of temperature, thus preserving a more level wire over the temperature range. Even so, the result is not as good as that obtained with a compound catenary.

With regard to tubular structures, even though—as the authors point out—they are much lighter, fabrication costs rule them out of normal two-track construction. There is also the big difficulty of galvanizing steel tubes and the risk of explosion.

In Fig. 6 it would be clearer if the description "Foundation level after subsidence" were amended to read "Foundation level after subsidence and packing-up of track to original level."

The Pennines naturally divided the scheme into two halves, one construction unit being organized for the work on the Manchester side and another on the Sheffield side, each being independent of the other. Work on the overhead equipment was timed to keep in step with progress on the new Woodhead tunnel and all new signal work. Thus, the rate of post-war progress, even taking advantage of all work done before the war, was only 32 track miles per annum on the Manchester side and 28 on the Sheffield side. It should be made possible for one construction unit to proceed at not less than 80 track miles per annum. Low speed must increase costs, and such costs are pounced on with glee by those who advocate the retention of steam.

Since 1936, when the Manchester–Sheffield electrification was authorized, there has been the commencement of one new scheme, namely Shenfield–Chelmsford–Southend, during this year, consisting of 70 track miles, and the cancellation in 1951 for reasons of economy of 31 track miles on the central branch of the Manchester–Sheffield scheme: $70 - 31 = 39$ track miles of new work in eighteen years, including nearly ten post-war years. The net progress resulting from work authorized since the London and North Eastern decision in 1936 averages, therefore, about one route mile per annum. Whatever the reasons, such are the facts with regard to our country which we electrical engineers have to acknowledge.

Mr. H. H. Swift: I should be glad if the authors would say whether the 4 700 000 trailing ton-miles per single track mile per annum, mentioned in Section 1.2, is the present-day calculated density of traffic.

This electrification is unique since it is the first time in this country that regenerative braking has been used on a main line.

When the scheme was being planned the costs had to be kept down to the barest minimum. We flirted with the idea of regeneration but the price seemed prohibitive. At about that time, Sir Nigel Gresley paid a visit to South Africa and came back full of enthusiasm and admiration for the regenerative braking on the Natal line, and suggested that this should be provided on the Manchester–Sheffield scheme if at all possible.

As an alternative rheostatic braking was looked into, but it was found that the weight of the locomotives would be considerably increased by the extra resistors required. It was also feared then that if the starting resistors were used to absorb the regenerated current, difficulties of heating might occur. I hope, after hearing the authors' description, that the trouble we feared in those days will not be encountered.

Could the authors give any indication of the number of times the resistance contactors in the substations have been operating. I rather anticipate that because the line to Manchester Central Station has not yet been electrified the Gorton resistance contactors at present may have been working much more frequently than was expected.

Would it be possible to have the costs in Section 2.2 segregated a little to show the spread of the cost of electrical engineering work over locomotives, substations, etc.? Segregation of the civil engineering figures would also be interesting to show the considerable cost involved in raising bridges and giving the necessary clearances.

I note that the authors have described the way the ring busbar arrangement has been altered in a number of substations to what they call the straight-line busbar. In the early days the operating department stated that the line would be in use 7 days a week, 24 hours a day, and to enable equipment to be isolated for ordinary maintenance and cleaning, the ring busbar was accordingly adopted.

The rectifier rating was, of course, specified prior to the issue of B.S. 1698. The test load was worked out extremely carefully from the duty expected on the more heavily loaded substations, and I am pleased to hear from the authors that very little trouble has been experienced from this equipment.

Are the resin-bonded glass-fibre registration arms, mentioned in paragraph (*e*) of Section 4.5.2, being used in conjunction with the normal insulator or will they eliminate the insulator entirely?

The structure-to-rail bonding, described in Section 4.6, is not similar to that employed on the Shenfield line, where a structure bond wire was run right through (because complete track-circuiting was installed from beginning to end of the route), whereas on the Manchester–Sheffield scheme, as shown in Fig. 6, the structures are bonded direct to the rail. With the revised signalling I should like to know whether this bonding method has been retained throughout.

As to Section 10 (Future Design Trends), I fear the authors are rather too optimistic in their remarks on power supply. We are not so fortunate as they are in Holland, where the Grid was designed with the idea of giving a supply to the railways. In this country the railways almost invariably have to provide their own high-voltage transmission cables from the Grid switching points to the traction substations.

With regard to locomotives, I would utter a word of warning against the adoption of the central-cab type. The sloping ends have to accommodate a great deal of equipment, but with this design both floor space and head room are very restricted. Likewise, the driver's cab tends to be noisy, particularly if compressors,

blowers, etc., have to be located close to the partition walls. Furthermore, the space for mounting pantographs is very limited. It is advisable to install pantographs as far apart as possible so as to reduce the concentration of load on the overhead line when both pantographs are in use.

Mr. F. Whyman: Many of us have contacts with our steam locomotive colleagues, and we never cease to hear how cheaply they make these complicated steam locomotives, weighing perhaps 120–130 tons, for £20 000 to £25 000 each. This is very good, and we always marvel at it.

One point in the paper I noticed with interest is an item for mechanical engineering work, £1 020 000. Is it possible to have details of that figure? If it deals solely with the cost of the mechanical parts, which I think weigh about 51 tons each on the $B_0 + B_0$ locomotive, that works out at about £15 000 or £16 000 per locomotive, spent on rather simple mechanical parts weighing 51 tons. In view of the low cost of British Railways steam locomotives this requires a little explanation.

My next point is of more importance. It deals with the flange wear on what I assume to be the $B_0 + B_0$ locomotive. The tyres are stated to require re-turning at 35 000–40 000 miles. This is indefensible on a locomotive of this type. A previous speaker has said in effect that the articulated type of locomotive is not to be preferred from a riding point of view and I quite agree. These locomotives, however, are not intended for high-speed running, and so far as I know they were deliberately designed to take advantage of the saving on tyres. They will give immense mileages between tyre turning on curving lines.

I have considerable experience of similar locomotives on track far more severely curved than the Manchester–Sheffield railway, and there no $B_0 + B_0$ freight locomotive with articulation is highly thought of if it does not do 70 000–80 000 miles between tyre turning on account of flange wear, and those now are rather antiquated $B_0 + B_0$ locomotives. Similarly, a $C_0 + C_0$ articulated locomotive on the same system does the surprising mileage of between 110 000 and 160 000 miles between tyre turning on account of flange wear. The same locomotive, on track which is predominantly straight, has in many cases covered 250 000 miles between tyre turnings. In these conditions, effective use can be made of electric locomotives, but with turning every 35 000–40 000 miles one of the main advantages of electrification is lost. The C_0–C_0 locomotive must be worse from the point of view of wheel flange wear than the $B_0 + B_0$, because it is not articulated, but it would appear that the benefits of articulation are not being obtained on the Manchester–Sheffield locomotives.

I believe that initially the design provided for an articulated joint with side spring-loaded movement, but the spring-loaded movement was found unnecessary and has not been used, the side movement having been packed solid. I think it will be found in time that the reason for these low mileages between tyre turnings is entirely due to the very flexible form of the bogie structure which flexes easily and therefore makes ineffective the inherent mutual guiding between the bogies on curves which is such an important feature of the articulated construction. If that structure were suitably stiffened (it could be done with one locomotive as an experiment if desired) I am sure there were be no difficulty in getting 80 000–100 000 miles between tyre turnings.

Mr. E. S. Cox: Figs. 10 and 16 show characteristic curves from which test-bed current consumption can be deduced. But this, I feel, is still a long way from the consumption values of those locomotives for which traction engineers everywhere have been waiting for a long time. What they would like to have is really very simple and consists of, first, a draw-bar-pull/speed curve, secondly the tracing on that curve of lines or contours of rate of current consumption appropriate to the different rates of doing work, and finally, the cost of current as supplied to the locomotive.

Values of that kind have appeared in test reports published recently for steam and Diesel locomotives. If such guidance could be given for actual electric locomotives, such as are now running on the Manchester–Sheffield line, it would be very helpful for dealing with the vast subject of economic motive power, and would help to avoid those rather unsatisfactory calculations and deductions we have had too long with us, based purely on thermal efficiencies.

I should like to follow Mr. Whyman in referring again to tyre wear on these locomotives. It puzzles me a little to know that the tyre-turning mileage is so low, especially bearing in mind the use of regenerative braking and the relief to wear of the tyre surfaces by braking blocks which should result therefrom. In this respect I assume it is just possible that this low mileage may be due to tread wear rather than flange wear. It would be interesting to learn whether this is connected in some way with the rather unsatisfactory adhesion conditions, and what the authors consider would be the best way to tackle this obvious problem.

Finally, in Section 10 reference is made to the very desirable ultimate aim, namely that all passenger traffic on electrified lines should be run by multiple-unit trains, leaving freight to be handled by locomotives specifically designed for that duty and not troubled with the complications of the steam boiler. I think the authors would agree that experience on the Manchester–Sheffield line points to that condition being only a final one, when the bulk of the lines in the country have already been electrified. For many years to come, where trains have to be picked up by electric locomotives and taken over from other forms of traction, the mixed-traffic locomotive and the boiler must be with us.

Mr. F. H. Beasant: First, in connection with the mechanical parts, there is the question of the fundamental change in design between the $B_0 + B_0$ articulated locomotive and the C_0–C_0 which is not articulated. This is of great interest. To be a little more specific about it, I should like to ask the authors if they could give any relative adhesion performances for the two locomotives under weight transfer conditions.

Referring to the $B_0 + B_0$ locomotives, I well remember that a great deal of consideration was given to the various mechanical and electrical methods of weight transfer compensation, and finally the electrical method of field shunting was adopted. I should like to ask whether this has turned out generally satisfactory in performance.

My next point relates to the difficulty of synchronizing movement in series and parallel working between the front and rear locomotives when working up a grade. Mr. Swift touched on this point. I was somewhat surprised to hear it was apparently impossible or impracticable to deal with this by some form of radio signalling between the two locomotives. Surely in these enlightened days of electronics some easy and practical system could be devised.

I seem to remember that in the original design no provision at all was made for air filtration. The desirability of having clean air arises from two main causes. First of all, we want to keep the traction-motor cooling ducts clean to avoid any reduction in their rating in service, and secondly we want to keep clean the commutators in the motors and the high-voltage control equipment in the high-voltage compartments. I have always felt that with force-ventilated motors, without filtration, the relatively high velocity of the air stream would carry the dirt through the machine ventilating ducts. It would be interesting to know whether this has been found to be the case, since the filters in the locomotives have been reduced or eliminated. In other words do the traction motor core ducts become badly clogged in service?

I was a little surprised to see that the total tare weight of the

motor coach is no less than 52 tons, and suggest that there is a good deal of scope for reducing that weight in future design trends.

Incidentally, there seems to be some mistake in the figures here or else in the figures in Mr. Swift's paper.* I took the trouble to compare the mechanical and electrical tare weights of the Shenfield stock with those of the Manchester–Glossop stock. The figures in the two papers would seem to indicate that the electric equipment weight is six tons heavier on the Glossop stock. I cannot believe that this is the case.

May I conclude with a general comment along much the same lines as Mr. Cock's. I have been working out the figures in a somewhat different way. The two electrification schemes which have been completed since the war represent a route mileage of only half of one per cent of the total route mileage of British Railways. This again emphasizes the development in resources which must be brought about when large-scale electrification commences.

Mr. H. N. Cox: I think most engineers concerned with transmission and distribution networks would agree with the idea, expressed in Section 10, that if, in any future railway electrification scheme, 33 kV cables have to be used, they should no longer be solid cables, such as were appropriate at the time the Manchester–Sheffield scheme was engineered; but there may be some surprise at oil-filled cable having been selected for special mention. I would ask whether oil-filled cable has been named for some specific reason or whether the modern gas-pressure type of cable should also have been mentioned?

Mr. H. Elder: The reaction of a visiting New Zealander to this paper is one of envy; the Manchester–Sheffield–Wath section is steep by main-line standards here, but similar gradients are found in New Zealand within 25 miles from the capital city, on the North Island main trunk line, and the two electrified systems are in many ways comparable. Of necessity, the paper deals very briefly with a number of problems, all of which invite further discussion.

The solid overhead construction, and particularly the mechanical independence of the overhead wires for each track, are well brought out in the paper. The risk of supply failure is also minimized by the use of a number of interconnected supply points, a more reliable system than the use of parallel feeders.

The duty cycle for rating rectifiers is interesting, but time-table variations over several years will materially alter the shape of the load curve. Is any advantage claimed for this method of rating over the British Standard method of specifying ratings for continuous loading, 1 h, 5 min, etc.? For the summation of load peaks the New Zealand Railways have begun to consider statistical methods, which may be just as accurate in the long run as a detailed time-table analysis.

I should like to know whether any trouble has been experienced with switching surges or other transient voltages.

The use of a negative earthing contactor is claiming our attention. The permanently-connected negative has the advantages of a solidly-earthed neutral in a.c. systems, and the contactor gives a measure of earth-leakage protection.

The use of power-operated isolators on the a.c. supply is interesting. Has their use on the d.c. side been considered?

The practice of controlling all circuit-breakers by supervisory control is well justified in New Zealand experience.

An alternative to the elimination of the auxiliary catenary proposed in the paper would be to increase substation spacing. Does the elimination of the auxiliary catenary cause any pantograph instability at high speeds? Trouble of this nature has caused the New Zealand Railways to lock down the front pantograph on each locomotive.

Pollution due to steam running is a serious problem; to combat corrosion the New Zealand Railways use a 10 in disc insulator with a long leakage path and large-diameter pin. Brass fittings have corroded badly in tunnels with steam working.

On the 45-min Wellington–Paekakariki run, locomotive boilers are not used, and passenger trains are pre-heated in Wellington Yard.

The paper recommends that 33 kV cables should be either buried or continuously supported. Would this recommendation apply also to 11 kV cables? The New Zealand Railways have gone to these methods to lessen the possibility of the lead sheath cracking when the cables are disturbed after they have taken a permanent set.

The paper also recommends that d.c. switchgear should in future be battery operated. Is this to keep high voltages clear of the control circuits, or is it due to the difficulty in feeding the closing coil of an open high-speed breaker when either side of it may be de-energized?

Mr. P. Bingley: The load cycle in Section 4.3.4 seems a costly way of proving that the equipment will perform a hypothetical duty, when it is borne in mind that it is the rectifier which is sensitive to the peak loads. The heating time-constant of the cylinders or bulbs is relatively short, so that loads lasting any appreciable time must be treated as continuous for rating purposes. On the other hand, the design of the transformer is influenced mainly by the long-duration loads, and here the designer can accurately predict the heating effect of such a duty cycle on rating.

I believe that an equal result could have been achieved by simply specifying a B.S. 1698 Class III rating with the addition of four times the rated load for 20 sec.

Further, it appears from Section 4.3.2 that overload protection is by instantaneous trips only. This means that the settings can either be low, in which case the elaborate duty-cycle cannot be met, or set above the highest peak (four times full load), leaving the equipment virtually unprotected.

Some time ago, when faced with a similar difficulty, I devised a low-cost relay* which would have a preset characteristic to match the rectifier rating.

If we are to reap the benefits of economical transformer design, improved protection is worth pursuing. Can the authors say what steps are being taken in this direction?

With regard to the filters mentioned in Section 4.3.4, it would be interesting to know whether these have proved adequate. Has the effect of cutting out the various tuned shunts been tried?

I believe the circuit-breakers (Section 4.3.5) are of the magnetically-held type. With such circuit-breakers, the calibration settings alter with variations in polarizing voltage and cleanliness of the (magnetic) pole faces. Has the dirt which caused difficulties elsewhere (Section 8.3) proved troublesome in this respect? Also, have any conclusions been reached as to the relative advantages of magnetically-held and latched circuit-breakers when installed in different (electrical) situations? It appears that the variation in calibration with polarizing voltage is sometimes, but not always, advantageous.

I do not understand why, in Section 13.1.4, the efficiencies of rectifiers and transformers are shown separately. The reference to 50° C is also intriguing. Is it the temperature of a particular part of the cylinders, and, if so, what is the significance of the choice?

As the equipment can only operate as a whole, it would surely be more informative to give only the combined efficiencies and to state additionally the significant individual losses at a reference ambient temperature which is met under normal conditions.

[The authors' reply to the above discussion will be found on page 185.]

* *Proceedings I.E.E.*, Paper No. 972, March, 1950 (97, Part IA, p. 42).

* British Patent No. 679422, 1952.

NORTH-WESTERN CENTRE, AT MANCHESTER, 7TH DECEMBER, 1954

Mr. A. H. Emerson: During the discussion at London, reference was made by several speakers to the low rate of progress of electrification in this country; they tried to create the impression that the construction work on the Manchester–Sheffield–Wath electrification was carried out at an exceptionally low rate. I think it should be pointed out that at least 80% of the construction work and commissioning of this scheme has been carried out since December, 1949, which, if worked out in the form of annual mileage, shows quite a reasonable figure, bearing in mind the difficult route which had to be followed.

Also, it must be pointed out that at least 75% of the work has had to be carried out on Sundays, as possession of the track for the erection of steelwork and wiring could only be obtained at weekends.

On electrification schemes abroad, undoubtedly much more latitude has been given to constructors of overhead equipment in the way of possessions, and probably on future schemes in this country the matter will receive more consideration with a view to speeding up the rate of progress.

Referring to the costs quoted in the paper, it would be interesting to have these broken down into some detail, in order that erroneous impressions might be avoided. For example: the costs of mechanical engineering work should be indicated: the mechanical part costs on locomotives, the cost of mechanical parts on multiple-unit trains, also the costs of the ancillary equipment purchased, such as water columns, etc.

A similar explanation of the civil engineering costs would also be of interest, particularly in view of the many hundreds of obstructions, such as drains, signal wires, etc., which had to be moved to erect the overhead-line equipment.

In the paper reference is made to the training of motormen. This was one of the biggest tasks to be undertaken by the E.T.E. Department, and so far a total of 618 men have been trained as motormen, assistant motormen or other grades on multiple-unit trains. These figures, broken down, are as follows:

Motormen	270
Assistant motormen	311
Other grades	37

There are still men to be trained before the programme is completed, and it is anticipated that there will be somewhere between 20 and 25 new entrants to be trained annually, as retirements take place.

I should like to draw attention to the high cost of painting overhead-line structures once the overhead equipment has been commissioned and energized on a main-line route such as that between Manchester and Sheffield. The painting of structures can only take place on the booms under isolation procedure, and it is not an easy matter to arrange for these isolations without seriously affecting traffic.

I should like to ask the authors if they anticipate new materials being employed on future electrifications to avoid the necessity to paint structures made of steel; e.g. prestressed-concrete structures have possibilities, if of a simple design. Possibly metal spraying or a high standard of galvanizing might avoid painting under maintenance conditions.

Reference is made also to pantograph lubrication. I should like to correct the impression given in the paper that grease is being used. The material being used on the Manchester–Sheffield–Wath system is wax graphite.

Much requires to be done by way of investigation in the future, regarding suitable materials for lubrication between the pan and the conductor of the overhead equipment. Good lubrication is required, which does not affect current-collecting properties of the pantograph, and at the same time consideration has to be given to the most suitable upward pressure of the pantograph.

On the Manchester–Sheffield–Wath scheme, the results with wax graphite lubrication are most promising, but comparison with other electrification schemes should be avoided in view of the duties the pantographs on this system have to perform. They have to work on overhead equipment which is subject to smoke blast from steam locomotives and often run over wires in sidings which are little used. This has a detrimental effect on strip wear. The wax-graphite lubrication is avoiding much arcing on bad wire, and the average mileage per pound of copper worn from the strips is higher than that on any other electrification scheme I know of at the present time.

The authors have made it clear that they hope to draw much discussion from their comments on future design trends. One could make a number of observations on the suggestions for the future, but I should like particularly to refer to bonding, which is not mentioned. I would ask the authors' opinion concerning the use of welding for bonding. It is admitted that to weld a bond to the rail undoubtedly gives the best result from an electrical-conductivity point of view, and probably it is a very sound job. Nevertheless, this method of attaching a bond to a rail brings into use a highly skilled man with his mate and lookout man, i.e. three men to weld the bond. This is very expensive. When bonding is installed on a new electrified line, no doubt this method is reasonably economical, but under maintenance conditions, when bonds become detached in isolated places, it is costly to have to send a welder and his team, with all their heavy equipment, etc., to attach odd bonds to rails. The pressed-in type of bond originally employed did not entail a skilled man being employed, or require so much apparatus, and it would allow the bonding to be maintained by one department only. I feel that the use of the pressed-in bond should be reconsidered with a view to obtaining simplification, and avoiding divided responsibility, at a cost of some technical perfection.

I should like to ask the authors' opinion of the suggestion made to use a continuous earth-wire between structures, to avoid the use of structure-to-rail bonds. This method had been employed on short distances in difficult places on the Manchester–Sheffield–Wath scheme, and undoubtedly it saved much expense in installing individual structure-to-rail bonds in such locations, and I think it might be adopted in many other places for longer runs to avoid welding bonds to the rail.

In Woodhead Tunnel a separate earth-wire was run as indicated in Fig. 7. This earth-wire was attached to the rails at approximately every quarter of a mile, which is quite adequate. Admittedly, it might result in slight strengthening of structures, but it ensures that this bonding, which is so vital in the protection system of the overhead-line equipment, is out of the way of any danger of breaking it from the rail or from the structure, and at the same time, once this is installed, it does not require to be touched for many years. So many loose welds or attachments to rails are avoided by this procedure.

Reference is made in the paper to the systematic method of maintenance of electric locomotives which has been adopted. I should like to add that a similar procedure has been developed for the substation equipment maintenance. The overhead-line equipment is patrolled in the same way as the track is patrolled by the permanent-way gang, and documentation for recording that this has been correctly done and that everything is in order is being developed.

The Manchester–Sheffield–Wath electrification is the first main-line electrification in this country where both passenger and freight trains are being hauled by electric locomotives, and

undoubtedly new technique for both maintenance and operation of the line will have to be developed over the years. The overhead-line equipment on the main-line portion of this scheme has to be energized seven days per week, and a great deal of planning is necessary in arranging for isolations and possessions of the track, to allow maintenance to be carried out on the overhead-line equipment or the track. For this reason, weekly possessions meetings with the operating department are very necessary; at these meetings the operating department make sure that all departments—i.e. permanent-way, signal and track engineers, etc., carry out their requirements in the section isolated electrically, to avoid unnecessary shut-down of sections of the line.

Mr. J. R. Pugh: In this paper the authors have referred to the dirty condition of the atmosphere and poor ventilation of the tunnels where these have affected air filtration on rolling stock. Mention might also have usefully been made of the corrosive effects of such atmospheric pollution on the overhead equipment, in particular at locations with low headroom, such as tunnels, where the situation is aggravated by the hot blast from passing steam locomotives.

During the post-war years a series of tests have been conducted to determine the resistance to corrosion of various metals and alloys, including aluminium, gunmetal, bronze and copper. In the same period, different paint treatments were applied to steel test-panels and exposed to the arduous conditions then existing in the Woodhead and Oxspring Tunnels. Previously, an atmospheric-corrosion survey of the line had been undertaken by means of the examination of rain water samples and measurements of the corrosion of mild steel. Resulting from these many observations, a specific paint treatment has been adopted for the protection of steels in the Oxspring Tunnel, where steam traffic may be expected to continue for some time. At other "black spot" locations, non-ferrous fittings have been preferred to steel fittings, and the paper suggests that this practice is to continue on future schemes.

Further use was made of the last months of steam operation through the Woodhead Tunnel to carry out flashover and resistance tests on many insulators of both orthodox and novel design. The insulators, supported on brackets from the tunnel wall, were not continuously energized; nevertheless a very interesting comparison could be drawn between the performance of insulators of similar rating but different design, and an indication was given of the probable value of suitable insulator cowls for future installations within tunnels subject to steam operation.

In Section 10 the authors state that future practice on British Railways will be to adopt registration from span wires. I imagine that for routes comprising four or more tracks a measure of mechanical independence will be retained between, for example, the main and goods lines. Perhaps we could be given some information on this point.

I believe others have spoken of the slow progress of railway electrification in this country since the authorization of the Manchester–Sheffield–Wath scheme in 1936, but looking rather to the future, there is little doubt that a settled programme for the large-scale electrification of main and suburban lines would enable British manufacturers to undertake the conversion to electric operation of up to 400 track miles per annum, i.e. a total of some 10 000 track miles in 25 years. The benefits of such long-term planning would be reflected in the economies to be obtained from the smooth expansion of industry, maximum standardization of designs and the fullest possible use of men skilled in this specialized field.

Mr. F. Whyman: I should like to make one or two remarks dealing with the subject of the electric locomotives. I have been rather surprised to see from the paper that it is intended to operate 850-ton trains up 1 in 40 gradients with two locomotives and up 1 in 100 gradients with one locomotive, but as I understand that this is a controversial subject you will not expect me to deal with it here.

I was recently looking up some old calculations dated 1937 which reminded me of the lengths to which we went at that time in our endeavours to make the 4-axle locomotive capable of dealing effectively with 700-ton trains on 1 in 100 gradients under the inferior adhesion conditions known to occur frequently on this system. After considering all the different ways of improving adhesion it was finally concluded that the use of a suitable mechanical design coupled with electrical weight transfer correction should make it possible to start and haul the 700-ton trains up the 1 in 100 gradient with the occasional use of sand under the more difficult adhesion conditions.

So far as I know the only change from the intentions of those days is that modifications to the proposed mechanical design resulted in adhesion conditions inferior to those anticipated with the different mechanical design at that time. Under dry conditions it was realized that there would be no difficulty in starting and running trains of greater weights than 700 tons, but it was appreciated that a heavy service can only effectively be operated under conditions where all trains can start and run under all conditions of adhesion and weather.

Again, I find that in many of the Tables in the paper, information is given on the tractive effort and current ratings of the $B_0 + B_0$ locomotives and the C_0–C_0 locomotives which gives a very inferior indication of the performance of the $B_0 + B_0$ locomotives. On looking up the records I find that this is due to the ratings for the $B_0 + B_0$ locomotives being based on the traction motor British Standard No. 173: 1928, whilst the comparable figures for the C_0–C_0 locomotive are based on the same specification modified in 1941 when the temperature rise for the continuous rating was increased from 105°C to 120°C for the armature windings, and to 130°C for the field windings.

As the construction of both types of motor is generally of the same insulation level and degree of excellence, I think it would be more helpful if the authors corrected their figures for the $B_0 + B_0$ locomotives to the 1941 basis.

During the formative stages of design of the $B_0 + B_0$ locomotives for this electrification, the question of using this type of locomotive for both freight and passenger service was discussed at great length, the question being whether a mixed traffic locomotive was the right solution. The conclusion then was that it was the right solution and it is interesting to see how this has worked out.

Considerable sacrifices have had to be made in the construction of the traction motor to make it of sufficiently wide field range to be a mixed-traffic locomotive, and if we compare the $B_0 + B_0$ and the C_0-C_0 locomotive motors, it will be found that they are of substantially equal performance, bearing in mind their different maximum road speeds, but that the $B_0 + B_0$ motor weighs 4·75 tons, whereas the C_0–C_0 motor weights only 3 tons. The latter is the more normal motor, having a modest and normal degree of field weakening, as the three motor combinations of this locomotive do not demand artificially large motor field range in that most of the 1·75 tons difference between these two motors is accounted for by the need to have a very large field range with the $B_0 + B_0$ locomotive having only the half- and full-speed combinations possible with this type of 4-motor locomotive.

In retrospect, the conclusion is, I think, that in spite of these very heavy motors, the mixed-traffic locomotive was the right solution for the Manchester–Sheffield electrification with its heavy grades and modest maximum passenger train speeds, but I think it must be easily recognized that its virtues are peculiar to this particular system, and that when electrification is con-

sidered for the more easily graded lines where higher passenger speeds are used, there will be no alternative to the C_0–C_0 type of locomotive.

Turning to the authors' notes on future design trends, I would say that whilst not having the support of all my colleagues on this point, I do feel that there is considerable virtue in simplifying the design of locomotives to have a single control cab, but this is only reasonably possible with locomotives not arranged for multiple-unit operation, and I would suggest to the authors that the central cab is inconsistent with multiple-unit operation, because ready access from one unit to another in service through central cab doorways is essential.

Use of vernier notching is extremely desirable; I would prefer to see it in the form where it is not normally used, but is available for use whenever adhesion conditions are found to be low.

The suggestion to use double-reduction gears could not, I think, give any economy in designs of this nature, as the maximum rotational speeds of the traction motors are readily used with single-reduction gearing where road speeds in excess of 40m.p.h. are contemplated, and the motors could not therefore be made smaller and only the additional complexity of double-reduction gears would be obtained.

Mr. W. T. Gray: Although an exponent of electrification I realize that it is not in the best interests to overcall a hand. One gets the impression that the originators of this scheme have done so in one respect at least, and that is the electrification of marshalling yards. The authors mention that a large percentage of the cost of overhead construction is absorbed in equipping these yards, and from a casual glance I can well imagine it. I should like the authors to express an opinion as to whether it would not be better in future to confine electrification to the main lines and to utilize Diesel-electric locomotives for shunting and marshalling services.

The use of a central cab should be approached with caution. The existing layout is the result of many years' experience. The whole of the h.v. eqipment is enclosed in a compartment which is fully interlocked and is accessible through a single door. Owing to the transverse arrangement, any part of the equipment back or front is immediately accessible once this door is open. The resistors are segregated from the switchgear, the switch compartment being itself pressurized by filtered air. The cables and connections are well spaced apart and follow the natural direct line from switch frames to resistors and motors. The switch and resistor frames are built as units so that for erection or overhaul they can be removed and dealt with as sub-assemblies. There is a great deal to commend such a layout for d.c. main-line locomotives. Central-cab locomotives are not new and the arrangement, while essential for shunting purposes, cramps the layout, cuts down accessibility and increases maintenance costs and the likelihood of trouble, particularly with a complex equipment.

I was interested in the authors' statement that they had found it necessary to have two pantographs raised to cope with the boiler load when stationary. I should have thought that a single pantograph would have collected the full load current of 240amp easily without trouble.

Mr. A. B. Washington: The electrification stretching over so many years as it has done, it is not surprising that traffic requirements have changed, necessitating reconsideration of many aspects in design and mode of operation; neither is it surprising that British Railways, together with the various contractors, have been able to meet such changed requirements, even after much equipment had been manufactured.

Without comment, for the paper is largely factual, I pass to the Section on future design trends of locomotives. I am surprised at some of the design features being considered by British Railways—for instance, a centre cab, and vertical auxiliary machines. The larger of these machines would have to be accommodated in the driver's cab for reasons of height. I can picture the driver, in such a cab, endeavouring to make himself audible to his assistant.

My next point can be classified under the same heading, but concerns an aspect which I have failed to discover in the paper, namely single- or two-man operation. Two-man operation is being worked on all locomotives at present.

For the actual driving, only one man is required, but various ancillary duties require to be carried out, and although these duties do not include firing a boiler, a second man is useful in sighting signals from the off-side of the cab, etc.

However, these locomotives are fitted for single-man operation, and this has necessitated—for reasons of safety—a multiplicity of extra equipment, both electrical and air and vacuum extras, with inshot valves, timing reservoirs, etc., all arranged to give automatic response to safety in case of the driver being incapacitated. The total extra weight and cost due to single-man operation must be quite appreciable—more than many might realize.

Now, single-man operation was considered a likely practical outcome when the locomotives were first designed, and hence the inclusion of this feature, but is it warranted for future designs?

If not, then much simplification could be achieved.

Mr. M. Marshall: From Fig. 3 it appears that the 33kV systems of the North Western Electricity Board and the Yorkshire Electricity Board could be coupled through the $0{\cdot}1\,in^2$ and $0{\cdot}15\,in^2$ 33kV feeders of British Railways. I should be interested to know what system is in operation to prevent this.

With the experience gained since 1941 with the first $B_0 + B_0$ locomotive "Tommy" on the Manchester–Altrincham line and in the Netherlands, has any notable alteration been found necessary or desirable, and is this locomotive still in action with the other locomotives?

The use of rheostatic braking has been tried with success, according to the authors, on one locomotive. Has serious thought been given to the use of magnetic track brakes on any of this rolling stock for emergency stops?

Could the authors explain the reason for the two voltmeters in series in the locomotive power diagram (Figs. 13 and 18)?

Has any consideration been given to the important question of telecommunications between the drivers and signal staff, using the 1500-volt contact wire and blocking condensers?

Has track corrugation been encountered since sections have been electrified?

[The authors' reply to the above discussions will be found on the next page.]

THE AUTHORS' REPLY TO THE ABOVE DISCUSSIONS

Messrs. J. A. Broughall and **K. J. Cook** (*in reply*): For convenience, we are arranging our replies to correspond to the Sections of the paper in preference to replying *seriatim* to each contributor.

Electrification Schemes.

Messrs. Cock, Crompton, Beasant, Emerson and Pugh refer to the length of time it has taken to complete the work; taking into account the aspects mentioned by Mr. Emerson, we do not find it possible to add to the explanation given in the paper.

The publication since the paper was written of the British Transport Commission's proposals for the modernization and re-equipment of British Railways, announcing large-scale plans of main-line and suburban electrification during the next 15 years, is perhaps the most welcome answer to the view that further electrification is long overdue and can and should be undertaken as quickly as possible.

We hope in our reply to later discussions to give fuller particulars of improvements in train timings and of current demand on its completion, and we hope also to be able to extend the encouraging particulars which Mr. Bird contributed to the discussion of the improvements in train performance.

In answer to Mr. Swift, the traffic-density figure is the present-day value and, as Mr. Bird mentions, does not differ materially from the initial figure, although it is differently expressed and there has been some shift in the flow of traffic.

Power Supply.

In answer to Mr. Marshall, locks are provided to prevent maloperation of the facilities for using alternative sources of power supply.

Transmission System.

In answer to Mr. Elder, the recommendation to bury or to support cables continuously would be equally applicable to 11 kV cables.

In answer to Mr. Cox, oil-filled cables were mentioned because of satisfactory experience with them in railway service, but it is expected that gas-pressure-type cables will also be suitable, although for the same cross-sectional area this class of cable has a slightly lower current-carrying capacity.

Substations and Track-Sectioning Cabins.

In answer to Messrs. Elder and Bingley, the advantage of stipulating a load cycle is that the alternations of light and heavy load can be arranged to conform at least generally to the service duty.

The relay Mr. Bingley mentions seems to have very interesting characteristics, although it must be admitted that simple overload protection has in fact given good service.

The filters have proved adequate.

Direct-Current Switchgear.

Conflicting views are held about the relative merits of latched and electrically-held circuit-breakers. Both have given excellent results in railway service, and the choice between them is of some difficulty. The advantages of arranging d.c. switchgear for battery operation are those mentioned by Mr. Elder, and the objection is additional cost. No economic use has been found for power-operated isolators on the d.c. side.

No trouble has been experienced with switching surges or transient voltages. Dirt troubles have not been experienced.

In answer to Mr. Swift, the resistance contactors in the substations have been operating over 100 times per week, mostly at the weekend. Modifications are being considered to reduce this figure.

Overhead Equipment.

Mr. Cock's warning on increased span lengths is appreciated, and only a modest increase is considered possible.

In answer to Mr. Swift, the use of fibre-glass registration arms is in the experimental stage, but it is hoped that the normal insulator will be eliminated.

In answer to Mr. Elder, compound-catenary construction is generally considered to give better results than the simple-catenary type for high-speed running.

In answer to Mr. Emerson, galvanizing and metal spraying are now being used to reduce the necessity for painting, but the prospects of prestressed concrete proving economically successful seem to be remote.

In answer to Mr. Pugh, mechanical independence is more expensive than span-wire construction and it will be used where warranted in special circumstances; unfortunately it is often impracticable where it would be of greatest service.

In answer to Mr. Gray, we think that Diesel-electric shunters should be used in future electrification schemes to the greatest possible extent to minimize the amount of wiring in marshalling yards.

Bonding.

In answer to Mr. Swift, the signalling arrangements are such that it has been possible to use the structure-to-rail bond method in most cases.

In answer to Mr. Emerson, each method of bonding has its particular application and is dictated to a large extent by signalling requirements as well as site conditions and relative costs. The short welded-copper bond is more economical overall than the pressed-in type, particularly with the present cost of copper.

Rolling Stock.

In reply to Messrs. Cock and Whyman, the articulated bogie construction of the $B_0 + B_0$ locomotive was chosen to suit the extremely heavy loads at low speed, when it is not detrimental to the track.

The riding of the C_0–C_0 locomotive, with six-wheel bogies, is naturally better at high speeds than the $B_0 + B_0$. Nevertheless, the latter has considerable benefit in cost of construction and satisfactorily takes turn and turn about with the C_0–C_0 engine on this line. There is certainly opinion both for and against articulation in various parts of the world.

In reply to Messrs. Cox and Whyman, the mileage between tyre turnings has, of course, referred primarily to the operation of Stage 1, which was a short haul of only 18 miles over the most congested portion of the line with much starting, stopping and heavy braking. Both tread wear and flange wear occurred, but the latter becomes the limiting factor. Speakers have made comparison with freight-train operation in other parts of the world where rolling stock is fitted with continuous brakes and thereby the brake wear is spread over the wagon tyres as well as those of the locomotives; with unbraked stock, all the braking effects are taken by the locomotive.

Although the handling of loose-coupled trains is being carried out satisfactorily without regeneration being available below 16 m.p.h., it would certainly be advantageous to have regeneration available to a lower speed.

Owing presumably to the effects of steam traffic and perhaps

to bad atmospheric conditions, neither lac nor special greases are capable of giving strip lives of 40 000 miles in this country; we have found that we get better all-round result with the special graphite grease or wax.

The standard quantity of steam per passenger coach for main-line trains to-day is 100lb/hour; and the maximum train is 11 coaches on this electrification.

In reply to Mr. Crompton, the mean pantograph pressure is 17lb at 16ft wire height.

In reply to Mr. Swift, experience on the latest S.N.C.F. locomotives shows that no difficulty need be feared of a central cab being noisy, and with suitable covers for the ends excellent accessibility can be attained. The comments of Mr. Whyman and Mr. Washington on this subject are appreciated. Single-man operation does introduce some complications.

In reply to Mr. Beasant, full particulars of tests to determine the adhesion characteristics will be given in a forthcoming paper by Dr. H. I. Andrews.

Weight-transfer compensation by field shunting has been used for the $B_0 + B_0$ locomotive and found satisfactory.

Regarding air filtration, during the experimental period some filters were removed for a time, but it became evident that some degree of filtration was necessary and the degree at present in use appears to meet the needs satisfactorily.

The weight of the electrical equipment of the motor coach stated in the paper is correct.

In reply to Mr. Whyman, the $B_0 + B_0$ locomotive has shown that it can start and haul trains of 750 tons up 1% gradient.

It is true that the $B_0 + B_0$ locomotive motors were designed to B.S. 173:1928, while the C_0–C_0 motors ordered later were based on the 1941 revision of B.S. 173.

In reply to Mr. Marshall, the veteran locomotive "Tommy" is being modified to line up where essential with the rest, which incorporate results of experience in Holland.

If an additional brake were considered necessary for emergency stops, rheostatic rather than magnetic track braking would be preferred.

Each cab has a voltmeter, and it is convenient to connect these electrically in series.

A system as suggested by Mr. Marshall is under trial for communication between drivers of locomotives on the same train.

We are not aware of any track corrugations over sections that have been electrified.

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Paper No. 1723
Oct. 1954

THE OVERHAUL AND MAINTENANCE OF DIRECT-CURRENT TRACTION MOTORS

By J. G. BRUCE, B.Sc., Member.

(*The paper was first received* 6*th April, and in revised form* 17*th June*, 1954. *It was published in October*, 1954, *and was read before* THE INSTITUTION 11*th November*, 1954.)

SUMMARY

The paper is a review of the maintenance practices mainly developed by London Transport for 600-volt direct-current railway traction motors. The paper describes the procedures adopted to improve reliability and the methods used to carry out heavy repairs after failures have occurred.

(1) INTRODUCTION

The first permanent electric railway in England was that opened by Magnus Volk on the sea front at Brighton in 1883; thus electric traction has not yet reached a century of service to the travelling public.

The first motors used on electric vehicles were open to the weather, commutation being effected by means of brushes made of copper gauze. This method was not very satisfactory, and it is doubtful if the d.c. motor would have been a success if the carbon brush had not been introduced about 1888.

In 1890 the first deep-level tube railway in the world—the City and South London Railway—was opened to electric traction, and it must have taken considerable courage on the part of those responsible to change to the use of electric locomotives from the originally-proposed cable drive.

The armatures of the traction motors for the first locomotives on this railway were built on the axle, thus providing a gearless drive.

It became evident very early in the history of electric traction that the open-type motor was unsuitable, and an enclosed machine, with spur gearing, was developed. The early motors of this type had four poles, two being wound and two being consequent; the motor frame itself was split, the two halves being in some types bolted together, while other types had a hinge on one side. Until comparatively recently many tramcars in this country were still propelled by motors of this type.

Commutating poles were introduced during the first decade of this century, and also ventilating fans, which allowed the capacities of the traction motors to be increased without increasing their size.

Improvements in the insulation techniques reduced the necessity for frequent armature changing; consequently box-frame designs superseded the split-frame types.

White-metal bearings were invariably fitted to traction motors until the introduction of ball and roller bearings in the second decade of the century provided a further means of improving their reliability.

In this country, when the term "traction motor" is used, it means almost invariably a d.c. machine. That it is a reliable and trustworthy machine is evidenced the world over by its universal use on Diesel-electric locomotives and by the continued search for a reliable conversion locomotive, so that alternating current may be collected at the contact wire but d.c. traction motors can be used to propel the vehicle.

It is common practice to mount a traction motor on the bogie of a motor-coach or locomotive so that a proportion of its weight is carried in suspension bearings by the driven axle, and the remainder of the weight by a seating on the bogie frame, on which a "nose" projecting from the motor case bears. The motor is therefore referred to, alternatively, as nose-suspended or axle-hung. To support the whole motor on the bogie frame is an attractive alternative, and several systems, including some in which the motor is mounted longitudinally and drives the axle through bevel or hypoid gears, have been developed. The arrangement involving longitudinal mounting is confined as yet to the lighter classes of vehicle.

The paper confines itself to dealing with the general case of conditions appertaining to the d.c. axle-hung traction motor and has particular reference to experience and practice as found on the railways of London Transport.

Maintenance of traction motors falls into three categories:

(*a*) Running-shed maintenance.
(*b*) Periodic overhaul.
(*c*) Repairs and modifications.
  (i) Repairs arising from service failures.
  (ii) Modifications to improve reliability and performance.

For the purpose of the paper these will be described, respectively, as maintenance, overhaul and repairs.

(2) MAINTENANCE

(2.1) General

Maintenance nowadays consists principally of inspection of commutators and brush-gear, including brush-changing where necessary, greasing and inspection of bearings and gears, and periodic testing of insulation.

(2.2) Armature Bearings

Until 1928, when the first armatures fitted experimentally with ball and roller bearings were purchased for service on the underground electric railways of London, all armature bearings were of white-metal. The metal used was generally one having a high tin content, and the bearings were kept oiled by a wool packing which required topping up at least once a week.

After an initial charge of grease when the motor is assembled, greasing of traction motors fitted with roller bearings is now carried out at a period of twelve months, when a fixed amount of grease ($1\frac{1}{4}$ ounces) is inserted from a special pump to ensure that the bearing does not run dry before overhaul. Trouble in motor bearings can often be attributed to over-greasing, so that control of the amount supplied, and of the period of supply, is a very important part of the maintenance procedure for traction motors.

The introduction of roller bearings produced a number of economies by the extension of the lubrication period, as well as an improvement in performance by a reduction in hot bearings. Following the initial tests, all new motors from 1932 onward were delivered with roller bearings, and all the motors already in service on multiple-unit passenger rolling-stock were gradually converted.

The time will no doubt come when a traction-motor armature bearing of the grease-packed roller type will be sealed from overhaul to overhaul, i.e. for four to five years, or 250 000 miles. Tests have, in fact, shown this to be possible, but as an armature-

Mr. Bruce is with the London Transport Executive.

bearing failure is both costly and possibly dangerous on multiple-unit rolling stock, some further research and testing is necessary to eliminate any risk of failure.

(2.3) Suspension Bearings

Until 1936, the axle-hung traction motors generally used white-metal bearings for the axle suspension. The quality of the metal used for this bearing varies considerably with the railway, some administrations even using a plain bronze bearing at this position in view of the relatively low speeds concerned. In recent years, London Transport have used the same quality of white-metal as was used for armature bearings, mainly to avoid any fear of contamination of the armature-bearing metal, which requires to be of superior quality and high tin content. In view of the fact that very shortly London Transport will have no traction motors at all with other than roller-type armature bearings, experiments have been conducted with a view to using a less-precious metal for suspension bearings without impairing the reliability.

London Transport introduced in 1936 the principle of clamping the traction motor to a suspension sleeve mounted concentric with the axle on a pair of roller bearings, and all motors delivered since that date use this type of suspension. Approximately half the motors now in service on London's underground system are suspended in this way. White-metal suspension bearings require repacking and oiling on a periodic basis. Oiling is now carried out every fortnight, but repacking takes place at approximately 40 to 50 thousand car miles, when the suspension bearing itself is usually changed for remetalling. This bearing change takes place at the time when the wheels are changed, not because bearing wear necessitates such attention, but to improve reliability and avoid failure, experience having shown that there is a danger that a bearing already bedded to another axle can be a source of trouble.

Bearing wear is generally greatest at the flanged end, and it is more marked where cast-iron blocks are used for braking. The cast-iron dust causes a lapping action between the bearing and the road-wheel boss on the side not protected by the gear case.

(2.4) Advantage of Fourth-Rail System

In the use of roller bearings, those railways using the fourth-rail return have an advantage over other systems, since the insulated return avoids any difficulties due to current being passed through the bearings. London Transport now use the fourth-rail system exclusively; although this practice has not been adopted directly for the purpose of assisting roller-bearing performance, it does avoid the necessity of providing special diverting brush-gear on the axle.

(2.5) Gears

In this country the main drive on multiple-unit stock with nose-suspended motors has been by means of a pinion driving a gear directly on the axle, with a ratio of between 3 and 4 to 1, depending on the requirements of the service and the stock. Straight-toothed gears were used almost exclusively until recent times, when single-helical gearing, having a tooth angle of $7\frac{1}{2}°$, was introduced to give quieter running. However, where helical gears have been used with white-metal suspension bearings, an increase in end-flange wear, both on the bearings and on the wheel bosses, has occurred owing to the movement of the motor relative to the wheels.

The introduction of roller-type suspension sleeves with limited clearances also allowed the use of a true lubricating grease in the gear cases in preference to a bituminous compound which was formerly used to reduce noise and to cushion the shock of gear teeth mating outside their pitch circles—a condition which arose from the clearances attained with plain white-metal-type suspension bearings. The new gear-case grease had to be carefully chosen, since it was found impossible to prevent leakage from the gear case into the roller-bearing housing. Contamination of the bearing grease by gear grease of the grade now used can be tolerated without detriment to the roller bearing.

Resulting from inexplicable short life experienced with a number of gears and pinions some years ago, it was decided that all gear wheels and pinions should in future be matched so that they constantly ran together. The view was held for a number of years that this was an important feature of good performance, ensuring even wear. The practice necessitated the removal of the pinion from the traction motor when wheels were changed and the pinion's retention with these wheels until they were refitted to another car and traction motor. As motored wheels on the London Underground have to be changed on the average every twelve months for turning, a lot of maintenance time was spent on pinion removal and refitting, with consequent damage to armature shafts and keyways.

Matching of pinions and gears has now been abandoned, as the cost of enforcing the practice far outweighed any advantage which might have resulted from the careful mating of the teeth, and it was found in any case that each gear wheel had to be fitted with at least one new pinion in its life.

On the latest type of traction motor, recently delivered, it was decided to fit pinions without keys in the shaft, and thus the fit is now more critical. It is consequently undesirable to keep disturbing this fit between the pinion and the shaft, as would have been necessitated by the continuation of mating. In general, therefore, the pinion is now only removed on overhaul.

(2.6) Commutators

Important maintenance work performed on traction motors, apart from the greasing, is the examination of their commutators and brushes. This work is carried out at the running shed at the normal equipment-inspection periods, which are at four- and six-weekly intervals, according to the age of the rolling stock. The length of the carbon brush allowed for wear varies on the different types of motor. From $\frac{3}{4}$in to 1in wear is usually allowed, and on a modern machine the brushes last at least about 18 months. It is now quite exceptional to have to change a complete brush-holder, although this was a frequent job when commutator flashovers were prevalent.

(2.7) General Insulation

When major defects occur on a traction motor, the best practice is to carry out repairs by specialists at a central point. This is the practice adopted by London Transport, the running shed exchanging the defective traction motor for a repaired one supplied from the central overhaul works at Acton. At the equipment inspection periods, however, an insulation test of the power circuits, including the traction motors, is made so that serious trouble can be averted by the warning of a low insulation reading. It is not considered good policy to allow equipment to continue in service if the insulation resistance falls below 2 megohms. It is rare for such a low reading to be due to the traction-motor insulation.

(3) OVERHAUL

(3.1) Selection and Recording of Overhaul

It is important to ensure that, when an elaborate system of routine overhaul has been instituted, work is not carried out unnecessarily. On London Transport the overhaul lives of vehicle and traction motor usually coincide. Occasionally, some motors will be received, on vehicles for overhaul, which are not themselves due for overhaul. It is essential, therefore, to maintain accurate records of all attention given to traction

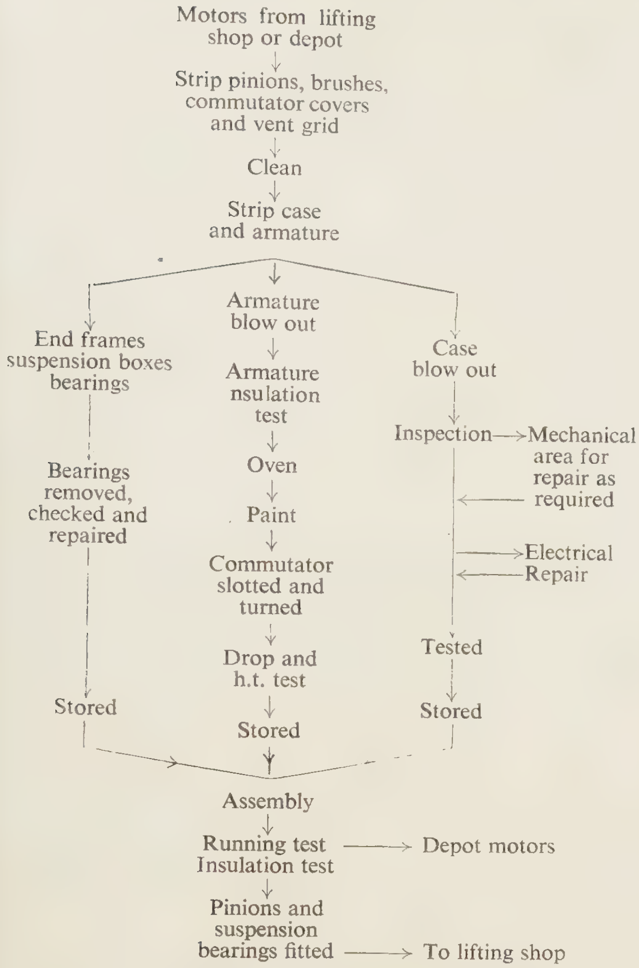

Fig. 1.—Diagram of normal overhaul procedure.

motors so that the history of a machine is readily available and unnecessary routine work is avoided.

Motors received in the overhaul shop when not due or nearly due for overhaul should have only the minimum of work carried out; cleaning, inspection and test without dismantling should be adequate. Care should always be taken to use such machines as replacements to the running sheds, so that there is more than an even chance that the actual overhaul life will not be unduly prolonged.

(3.2) Initial Cleaning

The first operation on a traction motor is to clean the outside so that it can be handled without undue contamination from the road dirt. Where cast-iron brake-blocks are used the road dirt includes, owing to the magnetic attraction of the motor case, a considerable portion of cast-iron brake-block dust. This dirt can be particularly sticky, especially where white-metal bearings, which require frequent oiling, are in use. The use of non-metallic materials for brake blocks and the fitting of roller bearings on both traction-motor armatures and suspension bearings reduces the cleaning problem.

Different methods of cleaning can be adopted. Steam cleaning, where used, should be followed by a drying process. Chemical means can be applied, such as the dipping of the complete motor in a trichlorethylene chamber, but this fails to clean off the magnetically-attracted dirt and some hand cleaning is still necessary. Although many of these chemical cleaners do not damage electrical insulation and are easily dried out, the total immersion of traction motors in a liquid or gaseous mixture has not found much favour.

At Acton Works the cleaning is done by hand, but special stands are used which are situated above a gridded floor, so that all the dirt removed falls below floor level; in this way the treading of this greasy dirt to other parts of the shop is eliminated.

(3.3) Removal of Detachable Parts

Following initial cleaning, the detachable parts of the motor, such as the commutator covers and brush-gear, are removed.

The commutator covers normally require little attention except to ensure that the catches, and safety chains where fitted, are in good condition. The felt seals require renewal from time to time.

(3.4) Pinions

The pinions, usually removed by an extractor tool before cleaning, are subsequently examined for excessive wear and checked for flaws. Flaws can be conveniently found on a magnetic crack-detector.

The pinions, having a rotational speed some three to four times as fast as their gear wheels, tend to wear out more quickly when made of the same material. Some manufacturers make the pinion of a harder material than the gear wheel so that its life will approximate more closely to that of the gear wheel. London Transport now use the same specification, calling for a heat treatment giving a Brinell hardness of 450 to 550, for both wheels, on the grounds that pinions are much cheaper to change and less costly to buy than gear wheels and the use of a harder pinion might reduce the life of the gear wheel. At the present time, a gear wheel lasts approximately twice as long as a pinion wheel, which has a life of over 500 000 miles. The shorter life of the pinion wheel is due not entirely to extra wear but also to fatigue failures which are found by the magnetic crack-detector.

(3.5) Brush Gear

It is in the brush gear that the variations in design of traction motors are most marked. There has been a constant endeavour to improve commutation and to ensure that motor failures are not due to trouble arising with the brush gear. Trouble on brush gear arises from breakdown of insulation of the supports, excessive wear on the brush boxes, or short brushes. The latter cause is a function of maintenance and should not occur. Insulators require critical examination and test before re-use, and gauges should be provided for checking the brush-box wear. Wear beyond standard limits should call for repair work to be executed.

Most of the serious troubles causing failures on brush-holders arise, however, from a lack of rigidity fundamental to poor initial design, and many brush-gear troubles can be minimized by ensuring that the fixings and supports are proof against vibration.

Brush-holders tend to accumulate a considerable amount of dirt which is largely composed of carbon and copper dust, and it is considered desirable to clean the holders thoroughly as well as the insulators. Shot-blasting is both an economical and an effective method of cleaning.

The working pressure of the brushes on the commutator is important; too much pressure will increase the wear of the commutator as well as of the brush itself, while too little will cause excessive sparking, leading to bad commutation, increased wear of the brush, and the possibility of a flashover. Brush pressures on traction motors require to be in excess of those generally found on stationary machines. A pressure of the order of 5 lb/in^2 is required on motors running on multiple-unit trains at relatively high speeds.

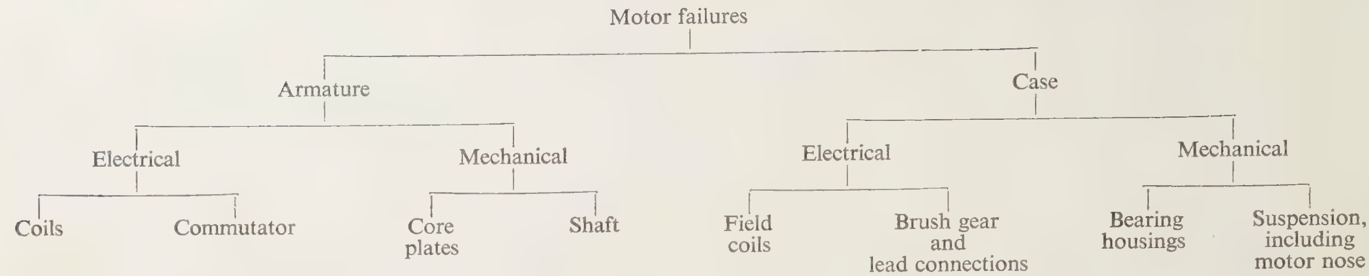

Fig. 2.—Categories of motor repairs.

(3.6) Dismantling the Motor

After external cleaning, the next operation is to remove the armature from the case. When the motors were of the split-frame type this operation consisted of "lifting the lid," but on modern machines the armature is drawn out from the pinion end. Special equipment is required to extract the roller-bearing races from their housings in the motor frameheads.

Internal cleaning should then be carried out, and special provision should be made for this if a number of machines are to be dealt with regularly, as the accumulated internal dirt is considerable. At Acton Works two special blowing-out containers are provided—one for the traction-motor cases and one for the armatures. The use of these boxes allows what is a comparatively dirty job to be carried out conveniently at the point where it arises, and inside the main shop, without inconvenience to other staff.

The plant for the motor cases consists of a hood with vacuum extraction assisted by the operation of a compressed-air jet. A settler is used to collect the dust before the air stream is allowed to pass into the open air. The armature-cleaning plant is connected into the same extraction system and is of similar construction.

(3.7) Roller Bearings

After removal, roller bearings should be thoroughly cleaned and inspected for wear.

The cleaning is usually carried out by washing in paraffin or white spirit, and automatic washers of the gramophone-turntable type are provided at Acton Works to carry out this job. The cleaning fluid is fed by force through the rotating bearing and is subsequently filtered and re-used. An air jet is passed through the bearings after they have been washed to dry them before handling. This process avoids any risk of dermatitis to the staff carrying out this work.

Bearing repairs were undertaken during the war years, races being built up by nickel deposition and oversize rollers fitted where excessive wear had occurred. Such repair work was expensive, and since this was only partially successful it cannot in general be justified economically when replacement bearings are available.

Bearing replacement is part of the routine overhaul, as there are always a number of bearings showing signs of scaling or flaking, and some even with chipped rollers. The life of bearings varies considerably; some have an exceedingly short life for no apparent reason, while others have been known to run 15 years completely trouble-free. Certain repairs can be carried out, especially to cages with loose or worn rivets, which will extend the bearing life, and certain types of flaking on the edges of rollers can be overcome by stoning.

The correct and careful fitting of roller bearings is an important prelude to a long life. Cleanliness is also an important factor, and at Acton Works special boxes are used for holding bearings after cleaning on the paraffin washing plant until required for refitting to motors.

(3.8) Motor Frameheads

The motor frameheads or end housings, after removal, require cleaning and stacking. Special stands are best suited for this, because frameheads are best stored on edge, each set then being easily available. As each framehead is usually refitted to its own motor case, any other way of stacking causes inconvenience.

Bearing housings in the framehead become worn or damaged by a defective roller-bearing, and it is a simple matter to machine out on a boring machine and fit a liner. This operation is, in fact, simpler than metal-spraying for restoration to size.

(3.9) The Armature

The armature, after removal and cleaning, requires inspection for the soundness of the banding, which should be renewed if there is any doubt. A repaint with an insulating enamel is also required. Vacuum impregnation is favoured by some to ensure that all crevices are filled with insulation. The practice at Acton Works is to ensure that all external crevices are stopped up with insulating putty, the whole armature then being painted with insulating enamel and baked for a period in an oven at 110° C without impregnation.

At overhaul the commutator should be skimmed. On machines where commutation has been found to be critical, turning with a diamond tool to produce an exceptionally good finish has been found to improve performance, but for normal-duty traction-motor commutators a high-speed-steel tool gives satisfactory results. The absolute minimum should be removed, as the life of the commutator can be shortened unnecessarily by taking too large a cut; usually about 0·01 in is sufficient after 200 000 miles' service, but it is, however, essential to ensure that all bars are cleaned up. Modern traction-motor commutators can now be expected to last the life of the motor.

Before the commutator is turned, the edges of each segment should be bevelled; slotting is then required, and this can be done by either a hand tool or a power-driven saw or circular cutter. The mica should be taken down at least $\frac{3}{32}$ in to allow for a possible 300 000 miles' service without further attention to the commutator. Automatic indexing machines have been used on this work and are satisfactory for a time on a regular flow of similar machines, but where adjustment of the indexing is necessary, to cover varying types of machine, difficulties are encountered. It is desirable to include an exhaust plant in connection with this work to avoid the mica dust being inhaled by the operator. Following turning, the slots require cleaning out, and this is best done with a hand tool.

Overhauled armatures should be given a high-voltage insulation test using alternating current at a voltage at least double the normal working voltage. A bar-to-bar "drop" test to ensure

that the joints and coils are in a satisfactory condition is also desirable. After test the armature is available for reassembly.

(3.10) The Motor Case

The term "motor case" is used collectively to embrace all parts of the traction motor which do not rotate, but usually refers, in particular, to the main magnetic frame. Wear takes place on the motor nose-seatings, and these require to be built up from time to time by welding or by fitting new manganese-steel wearing plates. These are riveted and welded to the motor nose, as there is a continual fretting action which occurs at this point and this will destroy the rivets as soon as any movement is allowed between the plate and the nose. The suspension housings, too, occasionally require special attention, usually arising out of a bearing failure; welding and grinding normally provide the necessary treatment. A case undergoing normal overhaul requires little electrical attention apart from an inspection for loose connections and a freshening-up with insulating paint. It is advantageous, as far as the motor cases are concerned, to use a light-coloured insulating paint, usually grey in colour, as discoloration will take place at any point where a defect occurs and make the source of any trouble easy to locate when repairs are necessary. If black insulating paint is used, it is sometimes difficult to locate the source of failure and unnecessary disconnecting and testing work may be undertaken.

(3.11) Reassembly and Final Test

It is usual to refit bearings and frameheads to the same case from which they were removed, although it is not essential to refit the same armature to the same case.

Following assembly, the completed motor is given a light test run. It is not necessary or desirable, even on a machine which has had extensive repairs, to give a Hopkinson power test, as is usually carried out at the manufacturer's works on new traction motors. It is not necessary after overhaul to prove the traction motor's characteristic; proof of proper functioning is all that is required. Testing the motor, with the field current controlled through a resistance and in shunt with the armature, will prove correct rotation and lead markings as well as revealing faulty bearings, indicated by overheating. Any undue noise or chatter will enable defects to be traced before serious damage ensues. The test run also allows the brushes to become partially bedded. Following the test, the pinion is fitted.

(3.12) Suspension Bearings

These bearings, when of the modern roller type fitted in a sleeve on the axle, become part of the wheel-and-axle assembly and therefore, not being part of the traction motor, do not come within the purview of the paper. White-metal suspension bearings, however, are part of the traction motor and are closely associated with it. The general work of remetalling the bronze backs with white-metal is a continuous process, requiring the use of metal-pots and moulds as well as lathes to machine the finished bearings. Distortion of the bearings sometimes occurs, but, provided the newly-metalled bearings are machined and kept in pairs, no difficulty arises. The bearings often wear on the edges, where the two halves join, and while it is possible to make good this wear with white-metal, this is not considered good practice as the white-metal tends to break up. The proper method is to repair by brazing and machining to size.

(3.13) Gear Cases

An important part of the nose-suspended traction motor is the gear case. This is usually provided in two halves which are bolted to each other and to the traction motor, and there are felt oil seals at the joints and at the axle holes. Renewal of the felt seals is regularly necessary. The old types of motor had cast-iron gear cases, but the modern types are usually made of light alloy. Fractures occur in these from time to time, but they can usually be repaired by welding.

(4) ARMATURE REPAIRS

(4.1) Electrical Failures

The most prevalent seat of trouble on a d.c. traction motor has always been the armature. In the early days it was always prudent to hold a number of spare armatures so that interchange could easily be achieved. While improvements in design and performance render it no longer necessary to carry a large number of spare armatures, and many modern armatures will, in fact, pass their whole life without failure, it is still true to say that the armature is the place where most motor failures occur.

It is frequently impossible to ascertain the real cause of armature failure. The breakdown of armature insulation, nevertheless, is still the end-result of most trouble on d.c. traction motors. This insulation breakdown generally occurs in the armature slots and may be due to any of several causes:

(*a*) Damage to the bar when winding, which usually shows up early in the life of the armature.

(*b*) Movement of the bar; this fault, which may take several years to develop, is more prevalent on long armatures.

(*c*) Burst armature banding; this was a frequent cause of excessive bar movement in early days, but it is now rare, although most armature failures have at first sight the appearance of burst bandings.

(*d*) Overheating of the bar; this fault may arise from local heating due to bad conductivity at a bar connection or to an overload arising from defective control-gear.

(*e*) Overstressed insulation; this fault can be accentuated by bad insulation, coupled with only slight over-voltage conditions or overheating.

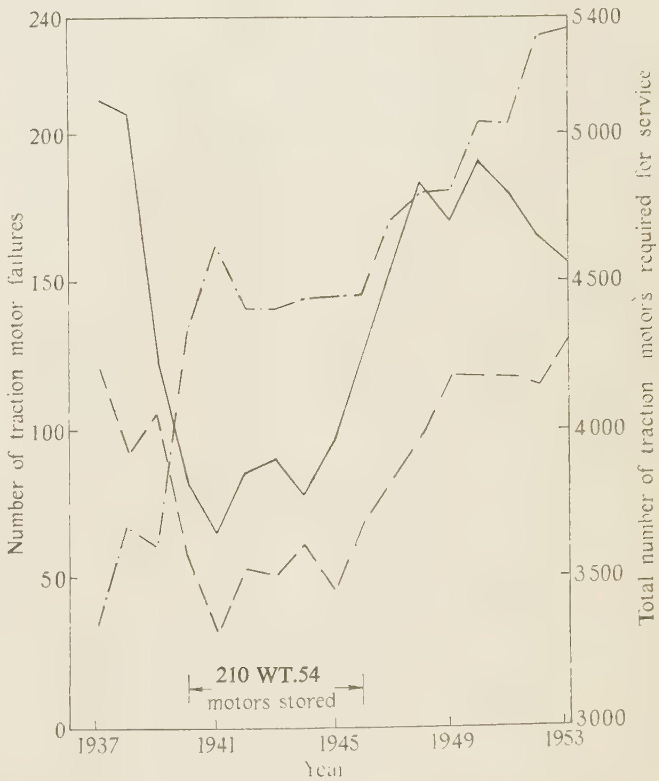

Fig. 3.—Armature failures compared with total motor electrical faults and traction motors in service.

—— Total motor electric failures.
— — Armatures rewound.
—·— Total traction motors required for service.

An insulation breakdown on the commutator is rare, and when it does occur it is usually secondary to an armature-coil breakdown, or follows bad flashing caused either by a brush-holder breakdown or by high-mica troubles.

(4.2) Mechanical Failures

Mechanical failures of armatures are usually associated with the bearings, and although the bearing is also associated with the motor case, the resultant damage and repair is mainly to the armature.

A bearing failure can be caused by

(*a*) Lack of lubrication.
(*b*) Over-lubrication.
(*c*) The use of the wrong lubricant.
(*d*) Collapsed bearing cage.
(*e*) Defective rollers and races.
(*f*) Bad fitting.

Each case will result in a hot bearing, with the possibility of seizure.

Armature shaft breakages are now very rare, but when they do occur they are invariably at the pinion end of the machine.

(4.3) Electrical Repairs

(4.3.1) **Rewinding.**

The main repair work on armatures consists of the process known as rewinding. Many electric railways throughout the world do not undertake their own rewinding repairs, preferring to return them to experts in the art—usually the manufacturers.

If the control of failures is, however, to remain in the hands of the operator, he must undertake his own rewinding. As the armature bar is the vital part of this process, the manufacture of these should also be undertaken. Depending generally on the price of copper, it is not usually found a good proposition to save the old armature bars for reinsulation; old bars can, however, be saved by careful removal, reinsulated and re-used.

The older types of d.c. traction-motor armatures had only two conductors per slot, and these were made as single bars, joints being made by clipping and soldering at the back end of the armature (i.e. the end furthest from the commutator). Although this method made manufacture of the bar easy and the armature could be wound in two independent layers, it had inherent disadvantages; in particular, since soldering was normally practised, trouble from bad joints was frequent.

The development of the evolute bar has eliminated the necessity for joints at the back end of the armature. Modern types of traction motor used by London Transport have a simple wave-winding with two layers of five bars in each slot, the wave winding having the advantage that only one pair of brush boxes is required.

The insulation of the armature coils after the copper has been formed to shape is most important, and until recently the only insulation suitable for traction-motor armatures was that which was classified as Class B insulation. The production of glass and silicone insulations has now provided a better, if somewhat more expensive, alternative, although to obtain high-quality insulation mica is still necessary. Designers should, however, continue to bear in mind that the most common and most expensive source of failure on a d.c. traction motor is the armature, and should allow liberal safety factors in armature design, especially with regard to the insulation.

The standard practice in insulating armature bars is to provide as much bar-to-slot insulation as possible, if necessary at the expense of the insulation between conductors. The voltage between bars on a 600-volt machine is small, whereas the voltage to ground can sometimes rise excessively. The main insulation is made up in sheets, which are wrapped around the bar and consist of a backing of rice paper, to which mica flakes are attached by shellac varnish. The secret of using this type of insulation is to use it freshly made; once the shellac is allowed to dry, the sheet becomes brittle and a tight wrap cannot be achieved, so that there is a danger that the insulation will be damaged as it is placed in the slot.

An advantage arising from the use of silicones in this process is that they can be provided in the form of tapes which can easily be wound on, thus giving a tight wrap. Some of these tapes are made of silicone-rubber, and this also provides a more flexible insulation which may well withstand some of the movement in the slot which has been the cause of breakdowns in the past, particularly on long armatures. The primary insulation on armature bars, for a satisfactory job, still requires the use of mica layers, but all carbon-producing media must be eliminated to achieve the principal advantage of silicones—that of improving the resistance to heat.

Another important point in the production of sound armature bars is the pressing. Frequent pressing at all stages of the work is essential to ensure that the maximum insulation is achieved with no voids and that at the same time the bar will enter the armature slot without damage. Hot presses have not been found necessary with either shellac or silicone insulations, provided heating in an oven can be carried out between pressings.

Following the placing of the bars in the armature slots a high-voltage test should be applied before further work is done. Usually for a 600-volt motor 2 500 volts from an a.c. supply is applied for 1 minute, and this test ensures a sound job. To ensure that the bars are down in the slot as tight as possible, a technique has been developed of using steel wedges pulled down by banding over the whole core length until there is no possible chance of further movement. This banding is then removed and the final banding wound on. It is considered by some that, as the tension of the wire used in banding is critical, elaborate devices are necessary to ensure that this tension is maintained within well-defined limits. All these devices rely to some extent upon the practice of the operator in any case, and an experienced bander who first ensures that the bars are fully down in the slots does not need a recording tensioning device.

Core bands are still preferred for normal-duty traction motors, since it is felt that a more solid result is obtained and that there is less likely to be movement of an armature bar which will result in failure. Where, however, peripheral speeds are high and the area covered by core bands has to be increased because of this, the resultant losses due to the steel banding wire may encourage the use of slot wedges.

The practice was developed at Acton Works of using tinplate strips with serrated edges under armature banding wire, and this results in a very solid finish securely held after final soldering. This practice has since been adopted by some manufacturers.

After banding, the bars are soldered to the commutator risers, and there have been several ingenious methods devised for carrying out this work as expeditiously as possible. The equipment in use at Acton Works consists of a gas-heated hot-plate through which the commutator is lowered, so that the commutator risers rest on the hot-plate, from which the solder is run into them. This process is materially assisted if the armature bar ends have been tinned before being wound into the armature, and it is also important for the solder to be one having a high tin content. After the armature has been baked in the oven for 24 hours and received its coat of insulating paint, a final high-voltage test at 2 500 volts a.c. is essential, followed by a bar-to-bar drop test to ensure that joints and connections are good.

After rewinding, it is essential to balance dynamically the complete armature assembly, including the fan. On some designs of motor some of the added balancing weights are carried on the fan, and this method, though convenient, requires the fan to be kept strictly to its own armature. On other types of machine a vee-shaped wedge on the end-ring provides the location for the required balance weights.

(4.3.2) **Commutators.**

Although commutator insulation failures are rare, repairs are often necessary, as commutators are sometimes severely damaged following armature coil failures or flashovers, bars becoming badly burnt at the edges. This burning is sometimes deep and necessitates the replacement of one or more bars.

New insulating vee-rings are always fitted when commutators are dismantled. After an armature is rewound, the commutator bolts are tightened both before and after the stoving of the armature.

In the early days of traction motors, bad commutation caused excessive wear to commutators, and this shortened their life. A commutator now generally lasts the lifetime of the armature, and it is rare for a traction armature to require a new commutator because of loss of size from periodic skimming.

(4.4) Mechanical Repairs

(4.4.1) **Shafts.**

The most serious mechanical failure which can occur to an armature is the breakage of a shaft, and this usually takes place between the pinion and the pinion-end bearing-housing—the section where the maximum stresses occur. Failures of this kind are very rare nowadays and are usually caused by a structural fault in the metal from which the shaft is made, or arise from some exceptional condition which causes over-stressing, as occasionally a shaft may break owing to the seizure of a bearing. The only possible repair with a broken shaft is the fitting of a new one; this usually only necessitates the use of a press after the new shaft has been correctly machined. If the core plates, however, are built up on the armature shaft and not on a spider, the armature will require to be completely stripped and rebuilt when a shaft is changed. This is one of the difficulties encountered when the designer of a traction motor has to sacrifice the spider in order to achieve a small size.

Bearing failures also cause other shaft troubles which require special attention. Where white-metal bearings are used a hot bearing will damage the shaft surface; the normal method of repair in these circumstances is to skim the shaft clean, refitting a white-metal bearing bored undersize. It is usual after re-metalling to replace the white-metal bearings in the framehead, and bore them *in situ* to suit the particular armature shaft to be inserted to ensure correct alignment. When roller bearings fail, the failure is often confined only to the bearing housings, and no repair is necessary other than replacement of the bearing. If, however, the inner race, i.e. the race on the armature shaft, rotates with respect to the shaft owing to seizure with the rollers, damage to the shaft occurs. A satisfactory method of repair is to fit a reduced-bore inner race after turning down the armature shaft to a substandard diameter. It is convenient to maintain a stock of standard undersize bearing-races for this purpose. At times the damage is more extensive and the shaft will not clean up to the reduced size required; if the shaft is large enough, further reduction to a second substandard diameter can be permitted, or a sleeve may be fitted to bring the shaft back to its original diameter for fitting a full-size race. When the shaft is of small diameter, a good form of metal deposition, such as nickel-plating, will be preferable, and this will normally necessitate the removal of the shaft. Normal metal-spray methods are not considered satisfactory for providing a seating for a bearing-race, as it is considered that there is a danger of the deposited metal hammering out.

It is an interesting fact that the larger bearings have a better comparative failure record than the smaller ones, which would seem to indicate that the provision of an additional safety factor in the calculation of bearing sizes might improve reliability.

Another source of special repair is the coned pinion-seat. Pinions until recently, in addition to being shrunk on, had a key fitted to ensure that rotation was impossible. The modern tendency is to eliminate the key and rely upon the shrink-fit to transmit the torque. Hot water or oil is used to provide the small expansion necessary to get a shrunk-fit on the coned end of the armature shaft. During the period when it was the practice on the Underground system to match the pinions with the gears, a large amount of pinion-changing was necessary, and the changing and refitting of keys in its turn brought considerable wear to the cones and the keyways. Repairs to the cones on the armature shaft are achieved by metal-spraying, and, when the keyway is defective, by the fitting of stepped keys. Reduced-bore pinions can also be used, with reduced-size shafts, when the matching of gears and pinions is not required.

(4.4.2) **Core Plates.**

When an electrical failure of an armature occurs, it almost invariably damages the laminations which are built up to form the armature core. These core plates are usually fitted to a cast spider which is pressed and keyed on to the shaft. If the damage to the laminations is severe, a new core has to be built up. The laminations, being punchings in soft iron, can be slightly irregular unless stamped out in a single operation; also, unless they are carefully fitted to the core and filed, the sharp edges will damage the armature bars when these are inserted. If special care is taken in assembling the core plates and the laminations are pressed up intermediately as well as finally, very little core-filing, if any, is required. It has also been found possible to add plates to the number originally fitted, by careful pressing and fitting. Loose core plates could damage the armature bars by allowing relative movement to take place, and could thus be the cause of armature failures.

(4.4.3) **Fans.**

Traction-motor fans on the older-type machines were sometimes made of cast iron and were frequently very heavy. Later designs were made of a light alloy, but both types are prone to failure by breaking up, and sometimes extensive damage is done to field coils and armature windings. Where the traction motor was liberally rated it was found possible to run machines without fans. In other types of machine the fan has required redesigning and replacement. The modern design of light-alloy fan, with vanes attached to a single disc, was found to fracture at the roots of the vanes. As this caused little damage to the electrical connections, these breakages were only discovered on overhaul, and satisfactory repairs were executed by welding the vanes and modifying the change of section at the root of the vane. Later designs of fan, as replacements, have the vanes shrouded. One possible cause of fan failures, which are sometimes difficult to understand, can be attributed to the out-of-balance effect produced by mounting the dynamic-balance weights near the periphery of the fan.

Now that it is possible to improve the temperature characteristics of machines by the use of silicone insulations, thoughts should be directed to eliminating the use of fans on normal-duty traction machines. Total enclosure is also a feature much to be desired, in order to prevent the ingress of dirt, particularly that produced by cast-iron brake blocks. There are, however, a

number of difficulties still to be resolved before this step can be taken without increasing the size of the traction motor.

(5) REPAIRS TO CASES

(5.1) Failures

The modern d.c. traction-motor case does not fail at the same rate as the armature. This may be due to two causes: the case is the static part of the machine not subject to rapid changes of forces, and space limitations of insulation are not usually so tight. Brush-gear design is, however, somewhat tricky, and badly-designed collection-gear can be a serious source of failure.

Insulation failures usually occur on cases because internal short-circuiting of coils has caused overheating which breaks down the external insulation. A failure of this kind requires the direct replacement of the coil.

Brush-gear failures can usually be rectified by changing the complete assembly of the brush-box and its associated insulator. Another source of failure is the leads, both internal and external to the case. Difficulties with the internal leads are rare, as adequate clamping arrangements are made. Damage to external leads, especially due to careless handling, is not infrequent, and modern motors have the leads carried in metallic armouring or tough-rubber sheathing, to help in eliminating trouble of this kind. It must always be remembered that in service the leads must necessarily undergo a considerable amount of movement and flexing as the bogies follow curvatures in the track, so that some natural wear must be expected; if, however, the leads are allowed to take up an unnatural position serious damage can result.

(5.2) Electrical Repairs

(5.2.1) Coils.

The normal type of d.c. traction motor has two types of field coil—the main coil and the interpole coil—and the principal differences between them are in the number of turns and the size of the loop.

In general, these coils are wound on a start-and-stop slow-operation winder with flat copper-strap, insulation being placed between turns and layers as required, and tightly secured. The completed coil is dipped in grey insulating paint after a preliminary heating and is then baked for 14 hours at 70° C. After this, the external sides of the coil are insulated with mica-shellac insulation ironed into place, and this external insulation is completed by taping-on a covering of asbestos cloth. The coil is then, after a preliminary bake of 2 hours, dipped and soaked in insulating paint, being finally baked for a further 14 hours at 70° C. On removal from the oven the coil is pressed to shape in a cold press, while still hot, and allowed to cool. A finishing wrap of asbestos tape is followed by a further two coats of grey paint.

Silicone insulations can now be used for the field coils also, insulations of this type having been used extensively in America as a means of up-rating the power output of existing motors. Some experimental coils have been successfully insulated in this way at Acton Works and are now in service.

The shape required of the final coil makes differences in the detailed insulation between turns, between layers and for the final primary insulation. Some d.c. traction motors have tapped or compound field-windings which also require differing detailed treatment of their insulation. The development of the field-divert type of circuit, with resistances in shunt across the main field to improve the speed range, has eliminated the need for tapped coils or multiple coils for this purpose. Nowadays, special fields are usually required only to accommodate special types of control.

A frequent source of trouble on traction-motor coils is the connection where the end of the strap is brought out of the coil. In some motors, copper strap, the same as in the coil, was often used to make the terminal by bending a piece of the required length to the required angle and riveting and sweating it into position on the coil. Breakages of this connection were frequent and various means were tried to eliminate the trouble. Insulated straps of iron, coupled with wooden packings, were used to bolt down these connections to the case. It was found difficult to maintain these securely, probably owing to the wood shrinking from the heat in the motor case, and the insulation chafed off the iron strap so that an earth fault followed. It became necessary to fit a more robust type of terminal, consisting of a cast lug riveted and sweated to the copper coil, and no clamping of the terminal was then necessary.

When the coils are fitted to the motor case, it is important to ensure that they are rigidly fixed. Vibration in a motor case in service is cumulative, so that any slight movement will eventually result in loose coils. Spring packings are used in some motors to achieve secure coils, but these themselves sometimes fracture, resulting in a loose coil.

(5.2.2) Brush Gear.

After some 20 years in service, brush gear requires extensive attention. Brush gear is not normally kept to its original motor, being continually interchanged from machine to machine, especially when failures occur. Severe burning often takes place on the brush boxes and repairs can be made by machining, followed by the brazing-on of new sections. Jigs maintaining the correct brush-slot size, as well as the distance from the fixing point, are essential when this repair is done.

Brush-holders should be provided with detachable front plates which can be cleaned up to eliminate wear, or renewed if necessary, while the box can be built up by brazing and machined back to size. If the original casting is not provided with a detachable plate, when wear occurs the front can usually be machined-off and a detachable plate fitted.

If the contact hammers of the springs holding in the brushes wear, these can be restored by filing, but care must be taken to ensure that spring pressure is not lost. The spindles carrying the springs and contact hammers often wear severely, and brazing and re-drilling of the casting are necessary.

The springs are usually shunted by means of pigtails incorporated in the spring carriers, while the brushes themselves are usually plain carbon blocks and rely upon current-transfer from the contact hammers. Some motors use a brush incorporating a pigtail, and the brush boxes on these machines seem to wear less, which indicates that some brush-box wear is associated with current transfer.

(5.3) Mechanical Repairs

Wear takes place on motor noses, and these are built up by riveting on a manganese-steel wearing plate and welding it round the edges. The suspension-boxes on an axle-hung motor are also subject to wear, especially where white-metal bearings are used. The bearing keys and keyways also require renewal. On London Transport, for example, the original WT.54 type motor, first installed in 1924, was provided with two keyways which were $\frac{3}{4}$in wide and 5in long. These subsequently wore, and were opened out to $\frac{13}{16}$in width. This widened keyway, too, eventually wore so that movement of the bearing was appreciable, and a change was made to a new $\frac{3}{8}$in keyway extending along the whole 9in length of the bronze bearing-shell. The key was then welded to the suspension box.

As this work was vital only when the keyway was badly worn and as it involved a considerable amount of machining, the work of modifying the boxes was restricted during the war years. The unfortunate result of this policy was that for a great number of years three different types of suspension bearing were necessary (one for each keyway), and as there were three standard diameters

of axle journal, a total of nine different fittings had to be carried at the depots for maintenance purposes.

Arising out of the current-collection arrangements necessary on London Transport, negative shoe-gear is usually carried by the traction motor, and supporting brackets are cast on the motor cases in appropriate positions. These brackets usually accommodate a pin of some form, from which the shoe-gear is suspended, and wear consequently occurs. It is a simple matter to bore and bush as required to restore to standard conditions, and the latest motors have been manufactured with the brackets already bushed to facilitate renewal.

(6) CONCLUSIONS

The present-day reliability of the traction motor is due in no small measure to the painstaking work of the designers past and present, but while the designer has an eye to maintenance considerations, his primary duty is to produce a machine in a competitive market. This ever-present concern may pull strongly in the opposite direction to the desirability of eliminating future repairs. It is hoped that there is food for thought in the paper which will result in a continuation of the improvement in reliability of the d.c. nose-suspended traction motor.

(7) ACKNOWLEDGMENTS

The author wishes to express his thanks to the London Transport Executive, and to Mr. A. W. Manser, the Chief Mechanical Engineer (Railways), for permission to prepare the paper and to publish the information which it contains.

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DISCUSSION BEFORE THE INSTITUTION, 11TH NOVEMBER, 1954

Mr. A. W. Manser: I should like first to draw attention to some features of the equipment to which the author has referred in relation to the severity of the service which they operate. It is not always realized that although these traction motors and equipments do not run very great mileages—only about 50 000–55 000 miles a year—the severity of the service is probably very much greater than anything to be found elsewhere in the country. We had our suspicions about the number of operations per day that were being performed by the traction-control equipment and other apparatus, and recently we carried out a test and found that, on an average, the traction-control equipments on the L.T.E. rolling stock operate about 900 times per day, and the brake equipment about 2 500 times per day, which is about three times what would be expected from the mileage which the stock runs. Account has to be taken of signal checks during the busy period of the day, for instance, which throw heavier duty on the traction motors and control equipment.

I feel that some points which the author mentions are worthy of further comment, and we might invite specialist opinion on them. The first is the question of roller bearings. The author has referred to the extraordinary variation in their life. In some cases they run for 15 years, whilst in another—admittedly an extreme example—the same type of bearing might crack up in 15 months. The bearings are fitted under the same conditions to the same machines by the same men and with the same care. If it were a question of the idiosyncrasy of a particular machine we would expect the failure to be repeated, but it is not. This indicates an unexplained factor which warrants closer investigation by bearing manufacturers.

The author also mentions vacuum impregnation, or rather the lack of it, in discussing practices adopted at the Acton Works. I think that vacuum impregnation has become, over the years, something of a fetish with electrical-machine manufacturers, and I am certain that it does not really do any good. I have always had my suspicions about it, and during the war I had the opportunity to see a number of machines stripped down which had spent varying lengths of time, from a few hours to a few months, under sea water, and in every case, salt had got into every conceivable crevice. If the machines had ever been sealed by a vacuum-impregnation process the salt could never have entered the places in which I saw it. We must accept the fact that we cannot seal the machine completely, and we have to adopt other methods to prevent electrical breakdown.

The author mentions commutator turning and the advisability in some cases of using diamond tools for providing a high finish on a commutator surface. Whatever tool is used, whether it be diamond, carbide, or high-speed steel, it is still necessary to exercise the same care to ensure that the commutator is not screw-cut; because, however fine a finish may be secured, if there is a screw-cut effect it is all wasted.

The author also refers to the use of roller suspension bearings. In addition to the technical advantages which he has mentioned, there is a considerable saving in cost to be effected by adopting roller suspension, because not only is there a saving on the white-metal bearings themselves, which are a very costly item to maintain, but there is also a saving on items such as the gearcases, because, with the precise maintenance of centres which is obtained with the roller suspension unit, it is possible to use a much-better-finished type of job than with the old white-metal suspension arrangements.

With regard to armature failures, and at the risk of being criticized by the author and being told that I am like the doctor who says that every death occurs through heart failure, I would add another item to his list of possible armature failures—carbonization of the insulation. I think that this is where the use of the silicone-type materials to which the author has referred is so very valuable. There can be no doubt that, particularly for a machine such as a traction motor which is on very arduous duty, and which is subject not only to frequent overload but also to an almost continuous cycle of expansion and contraction, many of the breakdowns result from carbonization of the insulation. In the course of time, owing to successive overheatings followed by expansion and contraction, breakdown occurs at the positions to which the author refers. The use of silicone materials is extremely promising, because it is possible to achieve a degree of elasticity with some which will take care of the expansion and contraction of the bars, and there is also a tolerance of overheating so that everything is not carbonized the first time the temperature rises towards 200°C.

I think that the paper is extremely opportune, because we have indications of a probable increase in the number of traction motors in service in this country, so that mutual exchange of

information on the basis of a paper such as this will, I feel, be extremely valuable.

Mr. H. H. C. Barton: I feel that the author has been too modest, particularly about the achievements of Acton Works and the contribution this workshop has made to maintenance and the art of specifying the best traction motor for a very difficult job.

It was not until the period of the First World War that the systems now forming part of London Transport obtained their first interpole motor, namely the 212 type. Up to that time they only had the 66 and 69 types. Only in 1920 did they get the first really modern motor in the form of the 260 type, which incorporated field tappings. This was so successful that it was among those subsequently converted to roller bearings, and it is still in regular service.

With the coming of the 1923–25 Tube stock, two other motors were introduced, namely the 152 and the 54 types. After a very sharp (but fortunately very short) period of initial trouble, these settled down admirably and were later also converted to roller bearings, which were specified for all subsequent machines. The 54 type of motor, with the 260, 152 and 212 types and for a period the 66 type on the Central Line, handled all London's traffic during the years between the two wars. At that time the operating department were continually cutting down timings and causing the annual motor-coach mileage to be increased. Very little coasting could be done in those days if the timetables were to be implemented. When the Piccadilly line was extended to Hounslow and Uxbridge the 54-type motor was subjected to shunt-field control, and is still surviving this well, although it is doubtful whether its designer even envisaged that weak field control would be applied to it.

Would the author give some more information about Fig. 3, because it seems that, after such a fine record before and during the last war, things began to deteriorate? I feel that this chart may not do justice to the more modern motors—I refer, of course, to the 100 type. It is significant that in 1939 there were only 16 armature winders at the Acton Works to maintain all the motors on the system. I was told by Mr. Manser that this number is still 16, although the machines to be maintained must surely have doubled.

With regard to maintenance equipment, it is not sufficiently realized that most of the special-purpose machines and plant which the author describes were suggested by the staff of Acton Works, designed in their drawing office and manufactured in their workshops. One of the first was a horizontal boring machine, which, incidentally, has been copied in many parts of the world. This device registered off the suspension-bearing housings and thus ensured a true parallel bore through the plain armature bearings used before the days of roller bearings. London Transport has given the world much information about the correct fitting of roller bearings, having regard to the diametral clearances of different types. It has developed unique handling equipment for components of awkward sizes and shapes, some exceedingly neat field-coil winding machines, and a speedy and efficient test equipment. Acton was probably the first maintenance workshop to insist on dynamic balancing of all rewound armatures.

Mr. H. Newsam: I believe that wheel-turning lathes are now available that can true up the tyres while the vehicle is fully assembled, and I wonder how this will affect the period that a motor will be required to run before overhaul. The overhaul of a modern axle-hung railway motor can usually be carried out when wheels are removed for turning, but we may have to design for much longer periods between overhauls. For the normal axle-hung motor the limit at present is probably defined by the sleeve suspension bearings. London Transport has pioneered roller-bearing suspension, and this should increase the mileage considerably before it should be necessary to take a motor off an axle. I should be interested to have the author's comments.

With regard to failures, I fully agree with the author that the armature is the part most prone to failure, and I feel that the new insulating materials, i.e. the silicones and others, can be very valuable in increasing the thermal life of the insulation so that the windings remain tight for a much longer period.

The author has mentioned the desirability of giving a rewound armature a high-voltage test. It is now possible not only to apply a high-voltage test to the whole winding, but also to test between conductors at more than the normal working voltage with various types of high-frequency or surge-testing apparatus. The use of this technique should assist in reducing failures in service.

There is no mention in the paper of the development of oil injection for the removal of pinions. The system can be applied successfully both to keyed and keyless pinions, but it is particularly valuable for the latter. I have heard of operators who have tried the keyless pinion and then decided it was not satisfactory because they experienced a few cases of slipping. With the keyless pinion it is necessary to take rather more care to ensure that the pinion is a good fit on the shaft, and it is usually desirable to fit the pinion with a rather greater interference. With the oil-injection system of removal this tighter fit need cause no qualms. I believe that oil injection is a very useful new tool, particularly for the maintenance engineer.

I must join issue with the author on the question of light-alloy fans. I have knowledge of such fans which have given trouble in service, but I also know of designs which have run under very severe conditions without trouble. This is an item which must be carefully designed, and I feel that the solution is not to dispense with the fan but to learn the lessons of experience and produce a design which will stand up to the arduous conditions of axle-hung traction-motor operation.

Finally, on the question of the conflict between first cost and maintenance cost which the designer has to face, there is a great deal of truth in the conclusion in Section 6. Can the author give, possibly as a percentage of the capital cost of the motor, an estimate of the average cost per annum of overhaul and maintenance, because this would indicate to what extent it would be worth increasing the first cost of the motor with a view to effecting a reduction in maintenance cost?

Mr. W. J. A. Sykes: I am interested in the author's comments on roller armature bearings and the experiments which he has been carrying out to reduce the necessity for frequent greasing. I am very surprised at the figure which he gives of 4–5 years or 250 000 miles without greasing. Are these really standard bearings and what type of grease was used? With the motors which I am responsible for maintaining, we have tried to increase the period between greasings, but have only been successful, up to the present, in attaining a reliable mileage of some 80 000 miles. We hope that we may reach a figure of 130 000 miles between greasings, but present indications are that that is the limit.

On the question of bearing washing, we have a very similar washing plant to that described by the author, except that we use warm transformer oil in place of paraffin and white spirit. This seems to do the job well, and obviates the care necessary to eliminate all traces of paraffin after washing.

I notice that helical gears were introduced for the sake of quieter running, but now that the white-metal suspension bearings have given place to roller bearings, I wonder whether London Transport has considered reverting to the straight spur gear, which is presumably cheaper. I also notice that commutator flashovers are referred to in the past tense. I congratulate the

Underground system on that fact, and I should like to know what the original spate of commutator flashovers was attributed to and the steps which have been taken to attain the present position.

With regard to roller armature-bearing failures, I am surprised that the author did not attribute the failures to the effects of the passage of current, but perhaps, since he does not use the running rail for the return current, he is not worried by that sort of explanation from the roller-bearing manufacturers.

With regard to the armature flash test, is it necessary or desirable to impose a high-voltage test on an armature with ageing insulation? Would not a 1 000-volt insulation test give all the information required?

I am most interested in the suggestion that the Underground system contemplate reverting to a totally-enclosed motor. I believe that amongst traction engineers of advanced views the former Southern Railway used to be held up to derision for using nothing but totally-enclosed motors. At present, while the Southern Region are trying to develop a motor which will run satisfactorily with ventilation, London Transport seems to be just as strenuously trying to return to the totally-enclosed type.

Mr. E. D. Wortley: With regard to the author's reference to Cardan-shaft drive motors, in which he states that this system is confined to the lighter classes of vehicle, I should like to quote the case of the Toronto subway vehicles, which have Cardan-shaft drive and a gross weight of 51·5 tons with a tare weight of 37·5 tons, as against London Transport surface stock with axle-hung machines having weights of 39·3 and 33 tons, respectively. I feel that an axle loading of nearly 13 tons can hardly be termed light, and there seems no reason why vehicle weights should restrict the use of Cardan-shaft drive with its advantage of a completely sprung traction motor.

My next point is with reference to pinions which have no keys. These have an obvious advantage from the design point of view, but in the author's experience have they shown an improvement in the life and a smaller number of fatigue failures?

With regard to the use of brush-holder liners, it would appear that this rather expensive item is only necessary because brush-holder pigtails are not employed. I cannot agree that brush pigtails are not normally used in traction practice, since, without them, apart from increased brush wear, there is a tendency for brush springs to overheat even though flexibles are fitted as indicated by the author.

The author's reference to core banding is interesting, since modern practice tends more and more to the use of slot wedges. This is not only on account of higher peripheral speeds and reduction of losses, but also to improve commutation, made necessary by increased armature loading and greater field range. The author refers to the use of only one pair of brush boxes. Does he attribute any flashover troubles to this cause, in spite of the relatively high brush pressure used? Whilst the figure of $5 lb/in^2$ mentioned in the paper is used on many axle-hung machines, it is possible to use a lower pressure on sprung machines such as are fitted with Cardan-shaft drives.

My last point with reference to the life of pinions and gear wheels. No mention is made by the author of the comparative gear life between machines fitted with roller and plain suspension bearings. It has always been assumed that the maintenance of gear centres is an important factor in gear life. Can the author supply any figures on this point?

Mr. W. E. Lewis: The author has referred to the increase in the factor of safety of insulation on armatures. The designer has to keep a check on the cost, since the design must be competitive. I suggest that the remedy is entirely in the operator's hands. There is no reason why he should not specify a higher voltage for the high-voltage test, and this has been done by some operators with satisfactory results. It will make the motor more expensive, however, and tend to make it larger.

The author refers to the variation in the life of roller bearings. These are assembled from components made to tolerances, and it will be obvious that the clearances in the running parts vary from bearing to bearing. Greases are now available which provide a controlled bleeding of the oil to a very marked degree, and which can keep the parts of the bearing continuously covered with a fine film of oil. If such greases had been used, I suggest that the bearings which gave short lives would have given considerably longer ones, and in fact, probably quite normal lives.

I agree with Mr. Manser's remark about vacuum impregnation. Some manufacturers, at least, dispensed with it many years ago.

I am surprised by the short life of white-metal suspension bearings. I should have expected a life of at least 100 000 miles from those bearings.

London Transport has done some very good pioneer work in the use of grease for the lubrication of gears. I was surprised to learn that the reason for using bitumen compounds was to eliminate noise to a certain extent, because I contend that any good lubricant should tend to eliminate noise. Has this grease been given an extensive trial with white-metal suspension bearings? If it is a true lubricant, as stated by the author, from which I would infer that it is superior to bitumen compound, there should be no more trouble with noise than when bitumen compounds are used. In any case, if the elimination of noise is important, I suggest that the best method is to use a resilient type of gear. I am sure that the use of resilient gears would also eliminate many of the armature failures, because there is no doubt that it has an extraordinary effect on armature life.

Mr. N. C. Kew: I am interested in the author's reference to the difference in wear between the more lightly loaded race remote from the pinion and the more heavily-loaded pinion race which did not show the same kind of wear or need so many changes. Some years ago it was stated* that with the lightly-loaded race the rollers can skid instead of revolving. This may give a clue to the difference in wear between the pinion race and the less heavily loaded race. The remedy suggested at the time was a slight preloading of the lightly-loaded race.

Mr. E. F. Hamilton (*New Zealand*): On the New Zealand railways, we are at present engaged in developing this question of electric-traction maintenance.

The author refers to the turning of commutators. Can he give any information on the speeds and feeds which are used? Mention has already been made of the necessity for not turning a screw thread on the commutator, and I quite realize that fact, but I should like to know the recommended feed.

Mr. A. W. Manser: The author has been taken to task because he stated that the use of the Cardan-shaft drive was confined as yet to the lighter classes of vehicle, and reference was made to the subway cars supplied to the Toronto Transportation Commission in refutation of this statement. However, the Toronto subway cars have a four-motor equipment with all the axles motored and the motors used are small (only 68 h.p.), although admittedly the vehicles themselves could not be classed as light. It seems to be assumed that the Cardan-shaft drive takes the whole mass of the motor off the axle, whereas in fact, with the Toronto subway cars, a gear case weighing 1 200 lb is carried on the axle instead of the traction motor.

Mr. R. Ledger: I believe that the standard London Transport gear case used at present is made of light alloy. It seems to have been extremely successful with roller-type suspension bearings,

* Smith, C. H.: "Needle Roller Bearings," *Journal of the Institution of Automobile Engineers*, January, 1936, 4, p. 47. Knaggs, M. J.: "Anti-Friction Bearings," *ibid.*, August, 1936, 4, p. 15.

but I believe that trouble has been experienced with similar cases where they have been employed with white-metal suspension bearings, probably owing to vibration resulting from the slightly incorrect meshing of the gears. Can the author give any further information on this point?

With regard to the trend on London Transport towards the totally-enclosed motor, I believe that they have gone part of the way by eliminating the usual ventilation through the motor core. Has this practice been justified, in view of the increased weight of motor which results?

I am interested to learn that new bars are introduced into a commutator to replace those burnt as a result of an armature failure or flashover. During the manufacture of a traction motor particular care is taken with the commutator to ensure that it will give satisfactory service, and it is considered preferable, particularly with modern high-speed machines, to avoid dismantling the commutator once it has been assembled.

In view of the fact that commutators now give little trouble, there should be sufficient metal on them to allow most defects to be removed by turning without replacing the damaged bars, except possibly where a motor has had the commutator badly damaged on a number of occasions. If this practice were followed I should expect that the cost of the few new commutators required would be no greater than that of the present practice of replacing bars, and the dismantling of commutators in order to fit new bars would be avoided.

Mr. G. Smith: The author mentions a brush pressure of $5 lb/in^2$. Am I to understand that it is the practice during running-shed maintenance to make tests of brush pressure and make adjustments if necessary during the life of the brush? In recent years there seems to have been a tendency for railways to specify an abnormally high pressure for a new brush, so that they do not have to adjust the pressure during its life. This seems to be the practice in the United States, where they commence with a pressure of 7 or $8 lb/in^2$, so that when the brush is fully worn there is still a sufficient pressure.

Does the author consider that the normal bar-to-bar "drop" test is sufficiently sensitive to detect the quality of joints at the riser connections? I feel that it is possible to have an armature which has satisfactorily passed a bar-to-bar "drop" test, but find, when it has been in service for a short time, that there is discoloration at the riser connections of one or two bars, indicating that there was not a 100% joint. Does the author feel that there is a need for some equipment which will indicate the quality of the joint, i.e. whether it is, say, a 50% good joint at the riser connections?

Mr. E. Webster: Mr. Kew referred to the large amount of wear on the commutator bearing compared with the pinion end bearing. There are two factors which may account for this. First, the commutator bearing, although it carries less load, is invariably smaller, so that relatively the load is not very different. Secondly, it is usually the location bearing, and if helical gears are used the thrust must also be taken on that bearing. Is the excessive commutator-bearing wear associated with motors which are running with helical gears?

Another speaker referred to the running of motors without core ducts and the resulting increase of weight. This is a fallacy. The reason for omitting the core ducts is that they become blocked before overhaul. Then either the motor must be run at a lower rating than it was designed for, or it must be made larger to produce the required rating.

Mr. D. E. Dodridge: It has been stated that the way to overcome wear on brush boxes is to fit pigtails to the brushes. One of the difficulties in the past has been to find a means of securing the pigtail in the brush so that it did not come out and cause flashovers.

The necessity for the use of pigtails really depends on the factor which determines when the brush is scrapped. If the side wear on the brush with no pigtails is insufficient to cause it to be scrapped before it is fully worn on the length, the fitting of pigtails, with the complication of clamps on the brush boxes and so on, is probably not worth while.

On one railway system, an experiment was tried of using copper-sprayed brushes which had no pigtails. It was found that if the copper spraying was on the top only, between the pressure finger and the brush, considerable heating took place there and the copper spraying tended to break up; however, if the spraying was extended half way down the sides of the brushes a good deal of the side wear was eliminated.

Mr. W. W. Maxwell: With regard to the use of silicone-insulating material, I believe that, particularly with totally-enclosed motors, conditions can arise which will lead to abnormal brush wear. Has the author had any experience of this? I understand that silicones have very low abrasion resistance, and in certain conditions brittleness can result. In the author's experience, has trouble arisen from this cause? Is it not possible that the expected increase in armature life, owing to the greater thermal stability and absence of carbonization in silicones, will not be realized because failure will occur owing to the poor mechanical properties of these materials?

Mr. A. G. Hopking: I would like to state how much we appreciate the way in which the London Transport Executive has, over the last 25 years, placed their experience at the disposal of anyone who is interested. I feel that British Railways generally have been able to take advantage of the vast experience of London Transport, and whenever any individual has wished to obtain some particular piece of information or to discuss any difficult subject, London Transport has always been extremely willing and anxious to help.

Mr. F. W. Roberts (*Canada: communicated*): Although the author's paper is, by implication, confined to the practices of the London Transport Executive, in places he surveys wider horizons. For example, in the Introduction he states that longitudinal mounting of traction motors with right-angle-drive gearing is confined to lighter classes of vehicle. While this is true of railways in Great Britain, it is not true of British coach-builders nor of foreign railways. Let us consider, for example, the rolling stock built in England in 1953–54 for the Toronto subway, and which has much in common with the R38 surface stock in London. The Canadian cars are 57 ft $1\frac{1}{2}$ in long and 10 ft 4 in wide, they seat 62 persons and are larger than those of the L.T.E. The steel cars weigh 83 470 lb and the aluminium-bodied ones 73 526 lb empty. This is by no means a lighter class of vehicle, but it has frame-mounted motors with their axes longitudinal and has hypoid gearing. This praiseworthy trend to remove from the axles the unsprung weight of approximately one-half each axle-hung motor is undoubtedly increasing; this has been the practice for some years in Switzerland and has recently been evolved in France.

Does the L.T.E. bed in new carbon brushes or do they find that modern machines are sufficiently stable to permit new brushes to be fitted square as received from the manufacturers? I agree that motor and brush manufacturers deplore the practice, but it avoids attempting a procedure which is frequently awkward and sometimes skimped on site. No ill effects have been noticed on 1 000 street cars in Toronto as a result of not bedding-in over a period of some years, nor on the recent 104 subway cars.

May I safely amalgamate various figures throughout the paper and infer that 0·75–1 in of brush wear in 18 months' service corresponds to about 75 000 miles and to 0·004 in wear on the commutators? If the figures vary with the age of the rolling

stock, I should appreciate data on recent designs such as the post-war R surface stock and the 1938 Underground stock motors.

Mr. S. G. M. Shallard (*communicated*): The variety of bearings in service on L.T.E. traction motors is part of the price which has had to be paid for progress. As each new motor was developed, some feature, whether of space or of performance, precluded the use of the same bearing as had run on its predecessor, and yet another bearing size went into service.

There is certainly here common ground on which the user, the motor manufacturer and bearing manufacturers can meet; but while at first glance it might be thought advantageous to make the first bearing to be used on a new design one with ample capacity in reserve for future development, there are a number of other aspects to be considered.

Fortunately for the designer, but unfortunately for the maintenance staff, a wide range of standard roller bearings is in general use from which the size most suitable for a new design of motor can be selected. The designer is therefore likely to follow this natural tendency without reference to the advantages of using parts which are already being stocked or worrying about what may be required five years hence, particularly if these matters are likely to influence adversely his current design.

The user does not lightly ask for a motor which will give substantially more power than his present requirements in an endeavour to ensure that he will not require a new size of bearing for a very long time. If he did, the power unit might be uneconomical for current requirements and disproportionately heavy for his vehicle.

The irregularity in bearing life is thrown into very sharp relief by the author's remarks. There is no complete answer to this problem, which has always made rather a mockery of elaborate bearing-life calculations, and recent studies of metal fatigue in general certainly confirm that even with the best materials there is still a very wide "life" scatter. Roller bearings are made of material which is more closely controlled for quality than most of those used in the electrical industry: the manufacturing processes are controlled by the tightest inspection which can be devised, the limits of manufacture are on a par with those of toolroom precision, and yet one bearing lasts 15 months and another 15 years, both on apparently identical duty.

Part of the answer may lie in the manufacture of the motor, and bearing failures attributable to misalignment, out-of-square abutments, out-of-round housings and other machining faults would become evident from the bearing history of individual motors. Part of the answer may lie with the fitters involved. It is not solely a function of their skill or their experience, but sometimes depends also on their patience at a given moment, whether they reject an unsatisfactory element such as a burred abutment or polluted grease. In fact, it reflects the human character in its most diverse moods. This is the same human element with which the bearing manufacturer has to contend.

Although anti-friction bearings have been used on traction motors for many years it is not often that one has the opportunity of studying the user's viewpoint on bearing performance. It is interesting to learn that the larger bearings have a better comparative failure record than the smaller ones, particularly when one bears in mind the modern tendency towards higher speeds with their increased lubrication difficulties. Such experience serves to underline the very valuable contribution which the user could make if close technical collaboration were established and maintained between the three main parties, i.e. user, motor manufacturer and bearing manufacturer.

Dr. P. F. Soper (*communicated*): The author states that new commutator segments are fitted to replace those which have been badly burned during service. Has any commutation trouble been found with such rebuilt commutators, since experience indicates that the surface of the new segments will, in all probability, have a different texture and condition as well as a different schleroscope hardness figure—this difference arising from the different seasoning and work-hardening conditions of the new and old bars.

Experience also indicates that the brush pressure should be maintained at a fixed value throughout the life of the brush, and that this should be the minimum compatible with mechanical stability. For a traction motor the quoted figure of 5lb-wt/in^2 seems to be a reasonable compromise, but this should be checked each time the motor is serviced. It is, of course, possible to design a brush-pressure mechanism in which the actual pressure exerted on the brush through its life does not deviate by more than a few per cent from the mean value. This arrangement is actually employed in one make of brushgear, but up to the present, it has not been used with traction motors, presumably owing to the fact that the severe vibration, the need for reverse operation and often poor maintenance necessitate a very simple robust type of brush-box and spring mechanism. For these reasons pigtails are a dangerous addition to the brush used on a traction motor, since, should the pigtail come loose, it may cause severe damage.

In addition to other causes, the commutator end-bearing may usually wear the most because the commutator is the hottest part of the machine. This appears to be a similar difficulty to that which occurs with tightly rated automobile-type generators, where a sleeve bearing must be used at the commutator end.

THE AUTHOR'S REPLY TO THE ABOVE DISCUSSION

Mr. J. G. Bruce (*in reply*): Mr. Manser draws attention to the astronomical number of operations required daily from traction equipments. The continual starting and stopping of London Transport trains must have a considerable effect on the performance of traction motors and be reflected in the failure rate as compared with machines on less arduous service. A high proportion of the failures of traction motors on rapid-transit service is undoubtedly a result of the frequent and rapid imposition of stresses, both electrical and mechanical, to the motors.

Roller-bearing performance on traction motors, although satisfactory, still leaves something to be desired. The failures are usually difficult to explain, since it is not easy to decide what is cause and what is effect. Closer investigation is proceeding, in closer co-operation with the bearing manufacturers, but considerable research will be required before any conclusions can be reached. The aim of bearing manufacturers and maintenance engineers alike should be "a million miles of trouble-free rolling."

It is not unreasonable to suggest that carbonization of class B insulation, resulting purely from ageing, will eventually result in a breakdown. This leads to the inference that even a good armature has a definite life, and so it would be an economic proposition to rewind it at a certain mileage to ensure further reliable service. However, this is not the experience of the L.T.E., which is that the expectation of life of an old armature is as good as that of a new one. The failure rate rises during the first 10 years of life and then generally remains steady, with a tendency to fall as the residue of prime-wound armatures gets older. Many armatures are now exceeding 25 years of life without trouble.

It is doubtful whether carbonization resulting from ageing is normally of a severe enough character to produce failure without an accelerating cause such as overstressing or overheating.

Mr. Barton has pointed out the historical sequence of some of the older traction motors still used by L.T.E., and it is, of course, examples of the GE.260, MV.152 and WT.54 types that are now exceeding the 25 years of service without rewinding.

With regard to the employment of armature winders on maintenance work, the number has remained at 16 over a long period, and not only has the number of traction motors in passenger service risen from just over 3 000 in 1938 to about 5 500 in 1954, but the number of auxiliary machines which have to be catered for has increased even more spectacularly. The chart in Fig. 3 shows armature rewinds at about 100 per annum for the 5 500 motors now in passenger service, whereas before the war the figure had only been reduced to about 100 per annum for 3 000 motors in passenger service. Just before the war the new L.T.100 traction motor, of which there was a complete batch of 1 760 machines, entered service, and this, together with the severe curtailment of the mileage run, brought the figure for armature rewinds down to about 50 per annum during the war years. The mileage run per machine, and the number of machines in service, increased after the end of hostilities, and the failure rate then rose from this low figure, but only to the level of the immediate pre-war period, with nearly double the number of traction motors which had been in service at that time.

Any large establishment concerned with the maintenance of equipment has to meet problems not envisaged when the apparatus was manufactured, and it is therefore obliged to develop special-purpose machines. The staff at Acton Works, since its inception, have been well aware of this, and development continues as new needs arise.

Mr. Newsam refers to wheel lathes which restore the wheel profile in position under the car. This is a logical development, and in conjunction with improvements in truck design, may well mean in the not-too-distant future that periods between inspection and overhaul will materially increase. For the present, however, the modern traction motor is not the limiting factor in the removal of the bogie for examination; motor wheels require retyring at about 200 000 miles, and the present motor bogie requires a light overhaul at half this mileage, if not earlier. In the L.T.E. we would be most gratified if the wheels ran for as long as the traction motor without the necessity of removal for attention. Normally every traction motor has to run with at least four different pairs of wheels between overhauls, which accounts in part for the abandonment of the practice of matching gears and pinions. Because wheel wear is the limiting factor, the provision of roller suspension bearings does not materially increase the mileage between car lifts. The principal advantage of the roller suspension sleeve is in the considerable reduction in white metalling costs, both in material and labour, and in the reduction of hot bearings and of lubrication costs.

It is interesting to note that developments are taking place in the provision of high-frequency testing apparatus which can be used to indicate the condition of an armature. If techniques can be developed to give a warning when an armature is in an unsatisfactory condition, without the danger which is always attendant upon using a high-voltage test (i.e. of making matters worse without actually locating the fault), a real step forward in the prevention of traction-motor failures will have been made.

It has not, as yet, been found necessary to use oil injection for the removal of keyless pinions on L.T.E. stock, nor has damage caused by slipping been found; this may occur in the future.

There is no doubt that a fan can be constructed to be trouble-free, but so far, such fans seem to be the exception rather than the rule, and with the introduction of silicone insulations, it is one part of the traction motor which might be eliminated.

Increasing the first cost of a traction motor, in order to eliminate maintenance costs later, is not a simple solution to the problem, since traction motors used on duties much lighter than those for which they were designed are just as prone to failure. The paper will have served a good purpose if traction-motor designers realize that the armature is vulnerable; where any doubt exists as to the action to be taken, the benefit of the doubt should be given to the armature.

Mr. Sykes raises the question of the length of service which is possible between armature-bearing greasings. Although it is prudent to fix the lubrication period at 50 000–80 000 miles with the present greases, the initial charge of grease amounts to about $1\frac{1}{2}$lb, whereas the topping-up required amounts to only $1\frac{1}{4}$oz. Therefore if the grease retains its lubricating properties, it should be possible to seal the bearings for an overhaul period of at least 200 000 miles. High mileages were obtained with standard greases in recent trials, but for the present the prudent limit is 12 months' running without topping-up.

The increased cost of helical over straight-toothed gears is not so much that the advantages accruing should be forgone, since in addition to quieter running, improved performance of the traction motor results from a transmission system which transmits an evenly-imposed torque. Straight-toothed gearing can produce cyclical forces on the armature shaft which may even be conducive to flashover.

Flashovers have not been entirely eliminated, but it is rare to have an epidemic of traction-motor flashovers without some knowledge of the cause. The improvement in this respect has been achieved by a combination of factors such as improved finish to the commutator, greater attention to the rigidity of brush gear, the general maintenance of brushes so that brush chatter is eliminated, in addition to the improvements arising from the use of modern switchgear.

Armature-bearing failures on L.T.E. stock can never be attributed to the passage of electric current, except as a corollary to a failure of insulation in the traction motor, and even then they are extremely rare. This is one of the advantages of the fourth-rail system of electrification.

It is considered that a high-voltage flash test can do quite a lot of harm which may go undetected and therefore leave the insulation weaker than it was before the test was applied; for this reason alone there is a considerable field of development for non-destructive testing of some kind. It used to be the practice to flash-test old insulation at 1 250 volts a.c., whereas rewound armatures were tested at 2 500 volts a.c. Since the use was adopted of an instrument which checks the insulation value as well as applying a potential test, old insulation is tested at 1 770 volts d.c. and new insulation at 3 500 volts d.c. The figure of 1 770 volts is, of course, the equivalent of the peak value of 1 250 volts a.c. (r.m.s.).

It is interesting to note the divergence of views on ventilation of a traction motor, but a totally-enclosed machine has attractive possibilities if the size and weight can be kept down.

Mr. Wortley raises the question of the Cardan-shaft drive and takes me to task for including the Toronto subway cars in the lighter class of vehicle. Although the tare weight of the Toronto cars is 37·5 tons, each car has four motors and the trains have no trailers in their make-up. Even on the lightest of L.T.E. trains each traction motor has to propel a much greater tare weight than 9 tons, and the application of Cardan-shaft drive would undoubtedly necessitate heavier gearing. It may be asked what is the purpose of producing a spring-borne traction motor of light construction, only to add an unsprung gearbox of nearly equivalent weight? The Cardan-shaft drive has its place in the development of electric traction, but the reduction in traction-motor weights has almost eliminated the need for its use, as the unsprung motor weight can no longer be a cause for anxiety.

It is too early to state whether the keyless pinion has an improved performance.

The use of two brush-holders instead of four makes the running-shed inspection much easier, and has not been considered

as a contributory cause to flashovers on 600-volt machines. It is not considered that a brush pressure of 5 lb/in^2 is undesirable.

Unfortunately, it is not possible to make comparisons of any value between gear life with or without roller suspension sleeves, as no exactly similar service has been performed. It is considered, however, that the advantage is slightly in favour of those running in association with roller bearings.

Mr. Lewis suggests that improvements in armature reliability must inevitably increase the size and cost of the machine. I do not accept this view. I want to have my cake as well as eat it! The improvement required is clearly marginal, since, out of a given batch of motors, about 25% will fail at some time in their life and these failures will invariably be in the armature. Therefore, if the designer decides that, whatever else he cuts, it must not be the armature, he will be on the road to eliminating the failures.

The short life of white-metal suspension bearings as indicated in the paper is due to the practice of renewing them at each wheel change, and does not arise froma failure of the bearing itself.

The provision of a good seal on the gear cases is also difficult where white-metal suspension is used, and a very thick grease is necessary if excessive loss is not to occur. The use of "gear shield," as the bituminous compound is known, may have developed from this defect as well as from the need to provide a cushioning effect where straight-tooth gears were mating out of their pitch circles, and there is no doubt that it was effective. There was not the same necessity to use the bituminous grease with helical gears, but a change was not made until contamination of the roller-bearing grease on the suspension sleeves occurred.

It is suggested with some diffidence that the traction-motor gear noise has been almost eliminated without the extra expense of fitting resilient gears. It is agreed that the quality of the transmission has a marked effect on armature life.

There is scope for much research on greases for roller bearings, but not all bearing failures can be attributed to lack of grease.

Mr. Webster refers to the bearing question again, and while there is no positive proof, since motors have either run exclusively with helical gears or indiscriminately with helical or straight, it is considered that the life of the commutator-end bearing is adversely affected by the use of helical gears. With reference to the question of the blocking of core ducts, the difference which this factor makes to the 1-hour rating of one type of motor, for example, is that the power is reduced from 168 to 130 h.p. The rating of motors without core ducts should improve the armature performance, since machines with ducts use them inefficiently for most of their life.

Mr. Dodridge points out that the pigtail brush has defects, which make it doubtful whether this method should be adopted. However, it does reduce brush-box wear. With regard to the fitting of a pigtail to the brushes, it is considered that damage need not result from a loose pigtail if the brush gear is designed to make the best of both worlds, and operate satisfactorily without pigtails. The use of pigtails in addition will thus improve the brush-box wear without bringing all the other troubles.

Mr. Maxwell deals with the question of increased brush wear with silicone-insulated motors. While this problem has not been seriously encountered as yet on traction motors in this country, it is understood that it has to be reckoned with where total enclosure is concerned. The difficulty arises from the moisture-repellent properties of silicones, which tend to remove the natural lubrication obtained from the moisture of the atmosphere, which assists good commutation. Without it the brushes become abrasive and wear out rapidly. This is, in a different form, the same difficulty as is experienced with rotating electrical machines in aircraft operating in the dry atmospheres at altitudes* above 20 000 ft.

* SIMS, R. F.: "The Wear of Carbon Brushes at High Altitudes," *Proceedings I.E.E.*, Paper No. 1505, July, 1953 (100, Part I, p. 183).

The mechanical strength of silicone rubber is lower than that of natural rubber, but it is considered that the resilience of the material in comparison with micapaper should result in improved general mechanical properties. Considerable advances have been made in improving the mechanical properties of silicone rubbers and varnishes during the last eight years, and there is no doubt that further improvements will be made in the future.

Mr. Kew infers that the commutator-end race is more lightly loaded, but this is unlikely, since the bearings are not by any means equal in size. The pinion-end bearing may be in fact be the more lightly loaded. The failures which occur on traction-motor commutator-end bearings are definitely not caused through skidding but frequently from chipped rollers.

Mr. Hamilton asks for information with regard to commutator turning at Acton Works on traction-motor commutators. Tungsten-carbide-tipped tools are used, at a surface speed of 600 ft/min, with 100 cuts per inch.

Mr. Ledger criticizes the practice of dismantling the commutator to insert a single new bar, but it is good practice when no trouble arises from it. Copper is expensive and should be conserved, especially early in the life of a commutator.

Mr. Smith raises the question of the maintenance of brush pressure. This is not checked at all during running-shed maintenance and seldom during overhaul, but it is considered that an occasional check should be made of reassembled brush-gear after repairs to springs and boxes in order to ensure that the brush pressure has not been either lost or increased. The actual brush pressure achieved is fundamental to the design of the brush-gear and to the original spring specification, and it is possible to design brush-gear so that the variation of brush pressures from new to worn is not great. The use of high pressures will undoubtedly accelerate the brush wear and should be avoided.

Regarding the "bar-to-bar" drop test, there is need for improved apparatus for locating invisible faults, but any apparatus which is developed must be simple, robust and inexpensive.

Mr. Hopking has very generously given an unsolicited testimonial. It is often instructive to have to tell others of achievements and failures, and this is at least one good reason why information should be exchanged.

In reply to Dr. Soper, no commutation troubles have arisen through rebuilding commutators with new bars. This rebuilding of the commutator is not a regular feature, but is only carried out when considerable damage has occurred to one or two bars in an otherwise satisfactory commutator. The number of traction-motor commutators treated in this way last year, for example, was approximately 50 out of over 5 500 motors. This is a very small quantity, and seldom has any further trouble developed on machines treated in this way. The repairs carried out on the L.T.100 type machines so far in 15 years' life hardly add up to more than one complete commutator a year.

Temperature tests on traction motors do not substantiate that the commutator is the hottest part of the machine, and commutator-end bearing wear cannot be attributed to this cause.

In reply to Mr. Roberts, with regard to brush bedding, after overhaul a complete new set of carbon brushes is fitted, but complete bedding is not carried out. The test run in the shop after overhaul is considered to be all that is required and has proved reasonably satisfactory. In the course of running-shed maintenance, brushes are changed indiscriminately as they wear to the specified limit, and the replacements receive no bedding whatsoever. This is also the practice adopted elsewhere.

Carbon brushes last approximately 75 000 miles and it is not unreasonable to deduce the equivalent commutator wear as very approximately 0·004 in.

Mr. Shallard raises the question of standardization, which is not given sufficient consideration. Designers and those con-

cerned with specifications appear to be mesmerized by the technical problem of getting the last ounce out of the materials at their disposal—usually, it must be said, with a view to overall economy in first cost and technical performance. Scant attention, however, seems to be paid to the maintenance engineer who has to live with their product for 30 years or more after they have proceeded to fresh designs. A little extra consideration in the use of an existing component might, in the long run, produce a greater economy, which in the welter of maintenance costs is not generally appreciated.

DISCUSSION ON "THE USES OF EARTHED SIGNAL CONDUCTORS ON TRANSMISSION CIRCUITS"*

NORTH MIDLAND CENTRE, AT LEEDS, 27TH OCTOBER, 1953

Mr. H. S. Moody: I have for many years been surprised that, whereas so much is said and written about the design and erection of overhead lines and also about protective circuits and equipment, little has so far been published about the associated problem of pilot wires and cables. This problem is often aggravated by a conflict between the desires of the overhead-line designer and the needs of the protection engineer.

On high-voltage distribution lines—in contrast perhaps with main transmission lines—telecommunication and fault-location indication are relatively unimportant; means for protective signalling and inter-tripping are the prime requirements.

We do not—in this area at least—provide any aerial earth-wire on any of our new high-voltage overhead lines, which are all of the unearthed type on wooden poles. Nevertheless, provided that the earthed signal conductor can be regarded, under the Overhead Line Regulations, as an earth wire or auxiliary conductor, as I think it should be, such a conductor could be added to a 66kV portal-type wood-pole line at comparatively little extra cost, since no additional pole height would be required, other than the 2ft increase at road crossings, and the poles themselves could presumably provide the insulation necessary. Even less line cost would be involved on the old type 4-conductor steel-mast lines, but the new pin-type 33 and 11kV lines would not be so readily adaptable.

The selection of the type of pilot described in the paper, in preference to one of the few alternatives at present available, will depend almost entirely on the cost and reliability of the end equipments. The cost comparison given at the end of Section 1.6 appears to cover line costs only. Can the author give the total costs, i.e. including costs of end equipments, so that a clearer comparison can be obtained?

Mr. H. C. Ogden: The paper suggests the stringing of another conductor on single- and double-circuit lines, and the voltage on this conductor might rise to an appreciable level above earth in certain circumstances, such as a fault on the system, atmospheric disturbances or accidental contact with other power lines. It seems to me that, particularly on double-circuit lines, another hazard would be introduced which would endanger men engaged on maintenance unless the signal conductor was earthed at the point of work in the same manner as the phase conductors. This would make impracticable the use of the signal conductor for communication purposes under these conditions.

What are the author's views on the safety precautions which would be necessary if a signal conductor were provided?

Mr. A. B. Gibson: With regard to the difficulty of applying the earthed signal conductor to the protection of double-circuit lines, there is the particular case of parallel feeders [Fig. 14(*c*)] where it might with advantage be used to supplement standard types of parallel-feeder protection. The inherent weakness of such systems is their inability to afford protection to one circuit when the other parallel circuit is switched out, but it is then that the signal conductor becomes effective.

A single-circuit line having a fourth fully-insulated spare conductor may in some instances be justified, where continuity of supply does not warrant a duplicate-circuit arrangement. The benefits to be derived from making use of such a fourth spare conductor, in the manner described in the paper, in the fields of protection, communication and fault location, may perhaps encourage the more frequent adoption of this scheme.

Mr. W. Casson (*in reply*): Mr. Moody has drawn attention to the fact that the communication-channel aspect of overhead line design has been neglected in the past. The earthed signal conductor is a new form of channel and Mr. Moody's suggestion for equipping a 66kV portal-type wood-pole line at comparatively little extra cost is very interesting and shows what can be done if the matter is actively pursued. On the total costs of providing the extra conductor and terminal equipment, some information further to that given in Section 1.6 is given in my reply to some of the earlier discussions. The best approach in this matter is to separate the line and equipment costs. The former will depend upon the method of construction, the type of conductor employed and the insulation requirements, which will be a minimum in the scheme suggested by Mr. Moody and a maximum for a double-circuit steel-tower line. The size of the wave-trap would depend to some extent on the maximum earth-fault current on the circuit concerned, but even in the worst case it should not cost more than, say, a few hundred pounds per circuit. The cost of the h.f. signalling equipment would depend upon the number of channels required, and would be anything from £100 for a single intertripping signal to £1 500 for a number of channels.

Mr. Ogden has pointed out the difficulties which might arise with a signal conductor if handled by men engaged on maintenance work. This difficulty would arise only on double-circuit lines, and could be overcome by earthing the signal conductor temporarily at the tower being maintained by a special portable earthing device. This would consist of the ordinary line earthing clamps and lead incorporating a series-connected wave-trap of very low impedance to currents of supply frequency but of very high impedance to currents in the band of frequencies being used for signalling. It is understood that such a device is used in other countries when work is in progress on overhead lines with carrier-current signalling through the line conductors.

Mr. Gibson has given an interesting example of the ways in which a spare conductor on a single-circuit line can be used for signalling purposes. Similarly, a double-circuit line, strung on one side only for power-supply purposes, can be provided with a signal conductor by stringing one conductor only on the other side, which can revert later for power supply when the remaining two conductors are added.

* CASSON, W.: Paper No. 1383 S, October, 1952 (100, Part II, p. 277).

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Paper No. 1737 U
Nov. 1954

A BRUSHLESS VARIABLE-SPEED INDUCTION MOTOR

By Prof. F. C. WILLIAMS, O.B.E., D.Sc., D.Phil., F.R.S., Member, and E. R. LAITHWAITE, M.Sc., Graduate.

(*The paper was first received* 15*th April, and in revised form* 16*th July*, 1954. *It was published in November*, 1954, *and was read before the* UTILIZATION SECTION 9*th December*, 1954, *the* SOUTH MIDLAND SUPPLY AND UTILIZATION GROUP 10*th January, and the* NORTH-WESTERN UTILIZATION GROUP 15*th February*, 1955.)

SUMMARY

A conducting sheet threaded by a magnetic field moving parallel to the sheet will assume a velocity equal to that of the field if it is free to move. The squirrel-cage induction motor uses this principle. The research described in the paper was initiated to discover what would occur if the sheet were constrained so that it could move only in its own plane and in a direction making an angle with the direction of motion of the field. It is found that, under certain circumstances, the sheet then travels at a speed in excess of the speed of the field. This phenomenon has been made the basis of a variable-speed brushless induction motor.

(1) INTRODUCTION

The chief merit of the squirrel-cage induction motor is its extreme simplicity, leading to great reliability and low cost. Its chief disadvantage is that in its simple form it is essentially a constant-speed motor. In order to provide variable-speed versions, two main lines of attack have been explored, namely pole changing and drawing power from or injecting power into the rotor. The first method yields a small number of discrete speeds, whereas the second may provide continuous speed variation, but at the cost of substituting a wound rotor and a commutator or slip-rings. There have been some attempts to make machines with mechanically-variable pole pitch, but such designs do not seem to have found favour. The present proposal has some relation to the pole-changing method, but does not involve any mechanical separation of the poles or switching of windings, nor does it require departure from the squirrel-cage type of rotor construction; there are in fact no switches or rubbing contacts.

(1.1) General Principle

The proposal arises from the recent upsurge of interest in "linear" 3-phase motors. These have been applied to the launching of aircraft and the pumping of liquid metals. In a linear motor the stator consists of a multi-phase winding of the kind used in induction motors but "developed," or opened out flat, as shown in Fig. 1. The magnetic field which

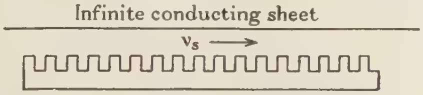

Fig. 1.—Principle of the "linear" motor.

previously had angular velocity ω_s now has linear velocity v_s given by

$$v_s = 2pf \text{ feet per second}$$

where p is the pole pitch in feet and f the frequency in cycles per second. If an infinite (but weightless) conducting sheet is placed over such a linear stator as shown in Fig. 1, eddy currents will flow in the sheet and drive it from left to right. If stator end-effects are neglected and if there is no resistance to motion the sheet will assume a velocity $v_c = v_s$, corresponding with zero slip. If there is resistance to motion, then the velocity will fall below v_s, there will be some slip, and power will be drawn from the supply. Conversely, if the sheet is driven by external means at a velocity greater than v_s, induction-generator action will cause power to be fed back to the supply. These statements, however, assume that the sheet is free to move in the direction in which the field is moving. Suppose now that the sheet is constrained to move along a line making an angle θ with the direction in which the field is moving, as shown in Fig. 2, which is a plan view corresponding with the elevation view of Fig. 1.

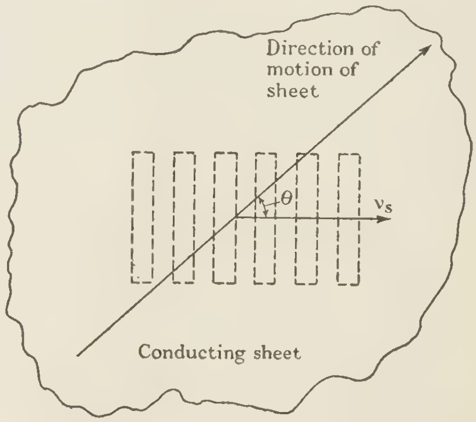

Fig. 2.—Plan view of conducting sheet and travelling field.

How fast will the sheet now travel? At first sight there are two alternatives. Either one resolves the synchronous speed v_s along the direction of motion, yielding,

$$v_c = v_s \cos \theta \quad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

or one resolves the motion of the sheet along the direction of field motion, giving

$$v_c \cos \theta = v_s \quad . \quad . \quad . \quad . \quad . \quad . \quad (2)$$

Both views found supporters, and it was decided to resolve the matter by experiment. All the early experiments showed a reduction of speed as θ was increased from zero, but the advocates of eqn. (2) were not easily discouraged, and it finally emerged that end-effects and poor torque had vitiated the first results, and that in fact eqn. (2) is appropriate, the sheet assuming, ideally, a speed in the predetermined direction such that its component of motion along the direction of motion of the field is substantially equal to the velocity of the field.

(2) A SIMPLE EXPERIMENT

The apparatus finally used for the preliminary experiment is sketched in Fig. 3. A copper disc was arranged to rotate between a pair of "square" linear stators wound to provide two pole pairs along the length. These stators could be turned

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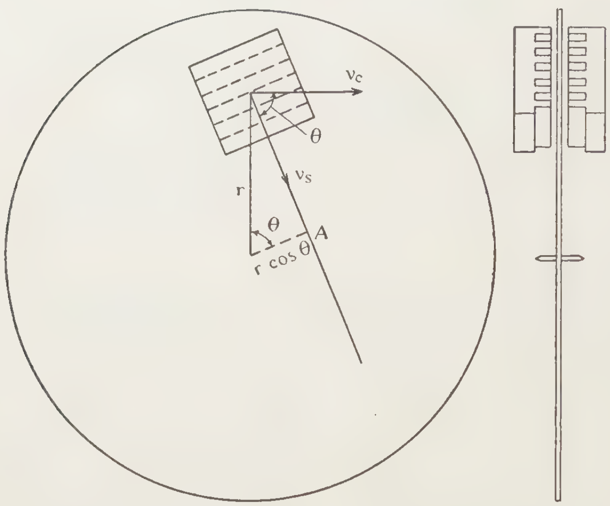

Fig. 3.—A simple experiment with a copper disc.

to make any chosen angle θ with the tangent defining the mean direction of motion of the copper under the poles. If the disc were to assume a velocity $v_c = v_s/\cos\theta$ at the centre of the stator, then the rotational speed would be $(v_s/\cos\theta)(1/2\pi r)$ and the time per revolution would be $(2\pi r\cos\theta)/v_s$. Now $r\cos\theta$ is the effective radius at which the linear thrust is directed, and is also easily measured. Fig. 4 is a plot of time per revolution

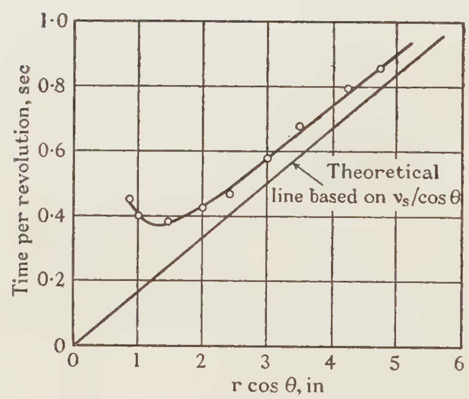

Fig. 4.—Results of the initial experiment.

against $r\cos\theta$ in inches. It may be seen that the experimental results show the expected slope, over a considerable range, but that the time per revolution is too great throughout. Furthermore there is a minimum in the observed time per revolution when the speed is about twice the minimum speed. A minimum is inevitable, of course, since as θ is increased towards 90° the torque falls to zero. This limit, however, is not reached in this experiment; there are other factors influencing the speed, for when θ is other than zero the copper has a component of velocity at right angles to v_s, and copper travelling in a magnetic field produces a braking force, so that there is braking present which becomes progressively more effective as θ is increased. Before proceeding to an assessment of this braking torque and a discussion of the methods by which it can be minimized, it is worth noting that apart from this effect the stator twisted through an angle θ produces the same speed as it would if it had been physically translated to the position A shown in Fig. 3. It could therefore be extended right across the disc without influencing the speed. It is also worth noting that at standstill the torque must be proportional to $r\cos\theta$, so that since, ideally $v_c = v_s/\cos\theta$, the product of standstill torque and maximum speed is constant and independent of θ. In other words, the machine has the properties of a constant-power device, being equivalent to a fixed-speed machine operating through a continuously-variable gear.

(3) END EFFECTS

Consider first a long array of alternate north and south poles stationary in space as shown in Fig. 5. A sheet of copper moving over these at speed v_r in the direction shown will give

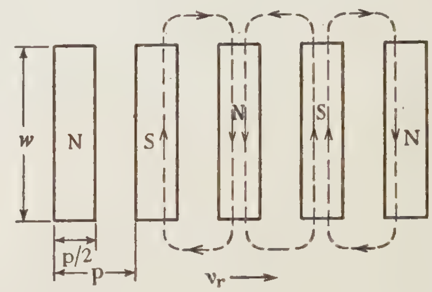

Fig. 5.—Eddy-current paths in a copper sheet under a moving field.

rise to eddy currents as indicated. The e.m.f. v_p generated under each pole will be

$$v_p = Bwv_r$$

where B is the flux density and w the width of the poles, and the resistance of the path under the pole will be

$$R_p = \frac{2w}{p\sigma}$$

σ being the conductivity of the sheet in mhos per square.

If the resistance of the path outside the poles is neglected, as it may be if the sheet is large, the current under the pole will be

$$\frac{v_p}{R_p} = \frac{Bp\sigma v_r}{2}$$

and the force per pole

$$F = B^2wp\sigma v_r/2$$

Now consider Fig. 6, which relates to the same pole array but with the copper moving at right angles to the previous direction

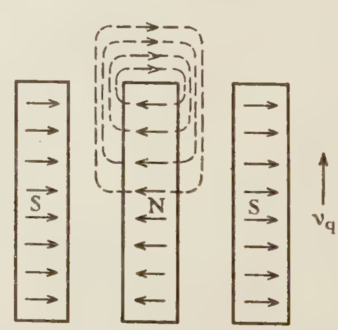

Fig. 6.—Eddy-current paths when the field is moving at right angles to the direction shown in Fig. 5.

at speed v_q. Now e.m.f.'s are generated under the poles given by

$$v'_p = B\frac{p}{2}v_q$$

and the path resistance "under the poles" is

$$R'_p = \frac{p}{2w\sigma}$$

so that if R'_p were again sensibly the whole resistance a current given by

$$\frac{v'_p}{R'_p} = Bw\sigma v_q$$

would flow yielding a force per pole of

$$F' = B^2 pw\sigma v_q/2$$

as before. But in this case it is not even approximately true to say that R'_p is the total resistance, since the eddy paths are as shown in broken lines, yielding a resistance very much greater than that of the part of the path "under the poles." Section 8 outlines an approximate evaluation of the forces in this case and in the previous one and results in a value for F/F' given by

$$\frac{F}{F'} = \frac{4w}{p}\frac{v_r}{v_q} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (3)$$

Turning now to Fig. 2, we may identify the moving field there shown with the fixed field just considered by subjecting the array of Fig. 5 to a horizontal velocity v_s, provided that in both diagrams the array extends indefinitely in the horizontal direction. In the absence of external drive to the sheet, v_r becomes negative and may be treated as the slip. This is given by

$$\left.\begin{aligned} v_r &= v_s - v_c \cos\theta \\ \text{Similarly} \qquad v_q &= v_c \sin\theta \end{aligned}\right\} \quad . \quad . \quad . \quad . \quad . \quad (4)$$

The corresponding forces F and F' will have components along the direction of motion of the copper of value $F\cos\theta$ and $F'\sin\theta$. The first will be a driving force and the second a braking force, so, assuming no other losses, the speed v_c will be given by

$$F\cos\theta = F'\sin\theta$$

or

$$\frac{F}{F'} = \tan\theta$$

or from eqn. (3)

$$\frac{4w}{p}\frac{v_r}{v_q} = \tan\theta$$

and from eqns. (4)

$$\frac{v_s - v_c\cos\theta}{v_c\sin\theta} = \frac{p}{4w}\tan\theta$$

whence

$$v_c = \frac{v_s}{\cos\theta}\left(\frac{1}{1 + \frac{p}{4w}\tan^2\theta}\right) \quad . \quad . \quad . \quad . \quad (5)$$

In this expression $v_s/\cos\theta$ is the ideal speed; the expression in brackets evaluates the loss in speed due to braking effects. This factor can clearly be minimized by making p/w small, as would be expected on physical grounds.

Fig. 7 shows v_c/v_s as a function of $1/\cos\theta$ for various values of p/w, calculated from eqn. (5). Fig. 8 shows the maximum value of v_c/v_s plotted against w/p. From these curves it may be seen that w/p should not be less than 4 if speed changes of the order of 2 : 1 are envisaged. For the first machine to which Fig. 4 relates, the maximum speed increase was 2·1 : 1 and w/p was 4. This is shown by a cross in Fig. 8 and is in fair agreement. The curves of Fig. 7 illustrate the cause of failure in the very early experiments; they were made with $p/w = 1$ with $1/\cos\theta$ in the region of 6. On Fig. 8 is plotted a curve of $(v_c/v_s)_{max} = \sqrt{(w/p)}$, and it may be seen that this agrees closely with the curve plotted from Fig. 7. It follows that $\sqrt{(w/p)}$ is a good approximate evaluation of the available speed range.

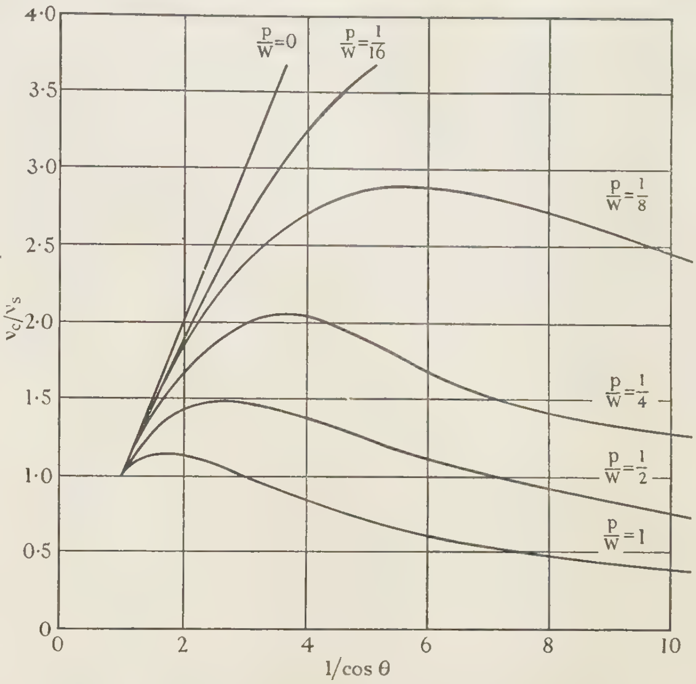

Fig. 7.—Theoretical speed curves for various values of p/w.

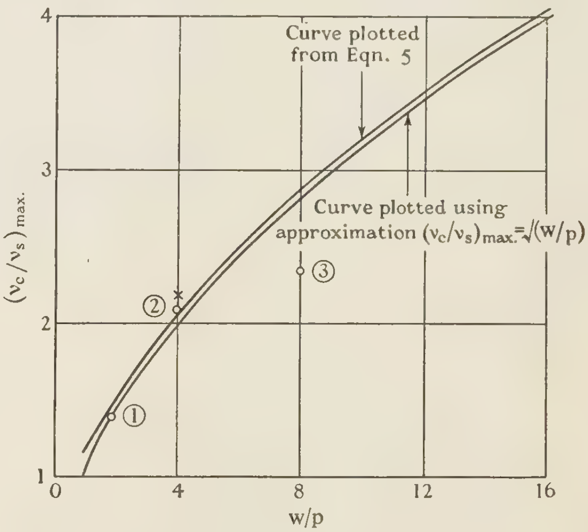

Fig. 8.—Theoretical maximum speeds as a function of w/p.

So far, the discussion of edge effects has centred on the pole ends, without reference to effects at the beginning and end of the stator array. Magnetic field is generated at the beginning of the array, travels along it, and then disappears at the end of the array. No mathematical approach to the evaluation of this effect has yet presented itself; experiments have indicated that it is much less important than the pole-end effect, and it will be left for the present.

(4) DESIGN OF AN EXPERIMENTAL MACHINE

The first machine used a plain copper disc and the efficiency was correspondingly poor; about 0·1% was estimated, with sensibly all the loss in the stator copper. It was therefore decided to make a second machine in which some more reasonable efficiency might be achieved. Two factors contributed to the low power output of the first machine: the large air-gap and the low speed at which it operated. The rotor had an outside diameter of 1ft and the stator sections were 1·5in square. The stator could not be made appreciably bigger because the surface speed of the copper, being proportional to radius, would have varied too much between the inner and outer edges of the stators. Furthermore, when the stators were angled in to increase speed, this situation was aggravated, and when θ was equal to arc tan 0·15 the inner edge was aimed direct at the centre and so could not contribute any useful torque. Since we have seen that w/p is required to be not less than 4, this gave a minimum of four poles across a 1·5in stator or a pole pitch of $\frac{3}{8}$in. At 50c/s this made v_s $37\frac{1}{2}$in/sec. The mean radius of the disc under the stator was just less than 5in, yielding a periphery of about 30in, so that, allowing for slip, a rotation speed of only about $1\frac{1}{4}$r.p.s. was to be expected with $\theta = 0$. Apparently the motor is better suited to higher frequencies than 50c/s, and it was decided that the next model should operate on about 500c/s.

The next line of attack was reduction of the air-gap. Assuming for the moment that iron can somehow be incorporated in the rotor, magnetizing current and stator leakage can both be reduced if the air-gap is made small, and leakage can be reduced by using a pole pitch that is large compared with the air-gap, and by spreading the windings. The stator copper loss can be reduced by increasing the pole pitch with a given pole-pitch/slot-depth ratio and a fixed air-gap. These well-known factors all call for a large pole pitch, whereas the $w/p \nless 4$ requirement, coupled with the limitation on w imposed by the disc radius, sets an upper limit to p. On these grounds a disc of large radius should have been used, but practical considerations indicated that about 6in radius would be as big as was reasonable. It was therefore decided to use 2·1in × 2·1in stators with 10 slots carrying a 4-pole winding, as shown in Fig. 9.

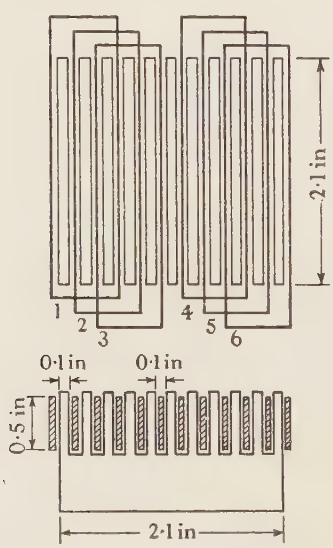

Fig. 9.—Practical arrangement of stator coils.

The next problem was the rotor design. This is required to conduct in all directions. A normal squirrel cage is useless, since the eddy currents must always be able to flow under the poles no matter what the angle of the stator may be. This is illustrated in Fig. 10, which shows that the induced e.m.f.'s in conventional squirrel-cage rotor bars would be such as to result in no current when the field direction is at the angle shown.

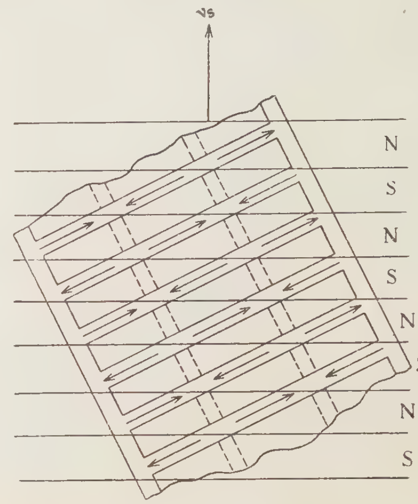

Fig. 10.—Induced e.m.f. pattern in squirrel-cage rotor.

Clearly, conducting paths, as shown by the broken lines, must be provided in order that rotor current may be allowed to flow. After several abortive attempts to produce a laminated rotor, it was ultimately decided to use a $\frac{1}{2}$in-thick copper disc of 1ft diameter impregnated with $\frac{1}{8}$in-diameter iron rivets driven into holes drilled through the disc; 1 200 such rivets were inserted as shown in Fig. 11. Both faces were then machined flat. The

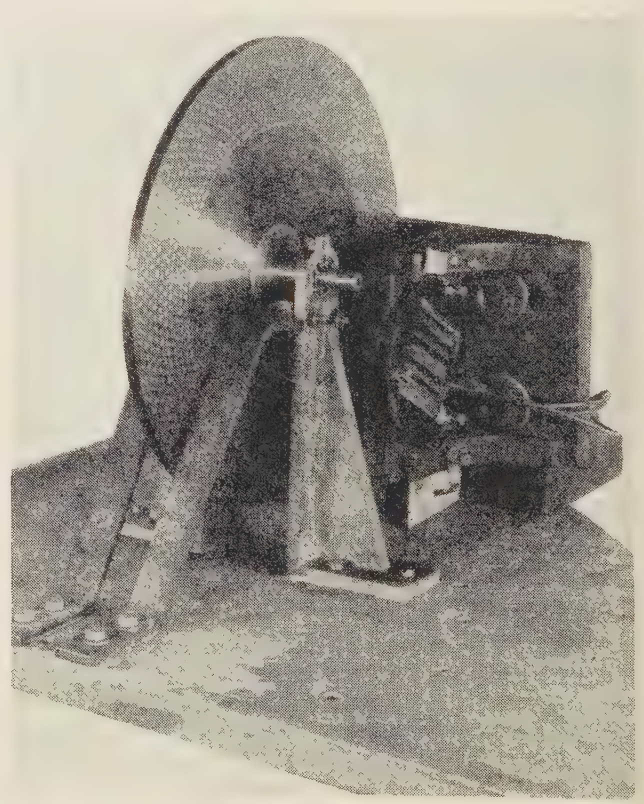

Fig. 11.—The first experimental machine embodying iron in the rotor.

rivet spacing and size were set by considerations of pole pitch, mechanical strength and workshop effort.

This rotor was set up in the machine shown in Fig. 11, provision being made to use the stator coils of Fig. 9 or any other stator coils not greater than 2·1 in square. The stator coils could be rotated individually in their holders to enable them to be kept in line at any value of θ. Supplies for the machine were arranged at 150c/s and 600c/s.

(5) EXPERIMENTAL RESULTS

The variation of speed with stator angle was tested first. The 150c/s supply was used because at maximum speed on 600c/s (about 2 400r.p.m.) the unbalanced insecurely-mounted disc was judged to be unsafe. The results are shown in Fig. 12. As was

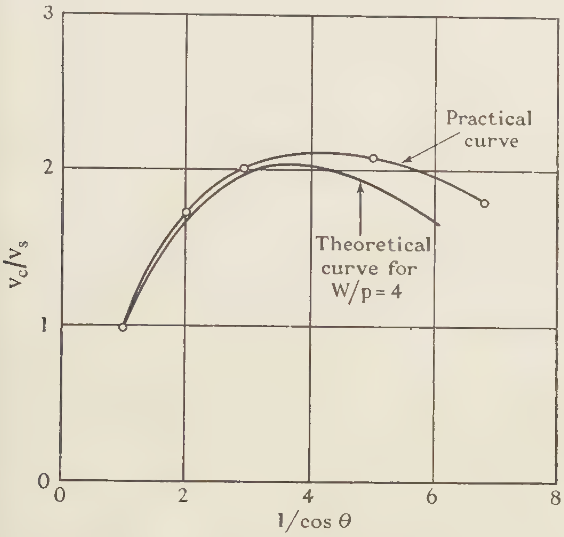

Fig. 12.—Speed variation obtained with the machine shown in Fig. 11.

expected, the speed range was about 2 : 1, and it may be seen that at minimum speed the slip was quite small.

Next, speed/torque curves were taken with the machine set to minimum speed, the 600c/s supply being used to give maximum power output. The results are shown in Fig. 13. This diagram shows the sort of characteristics expected of an induction motor: and standstill torque is less than the maximum torque, and the standstill input power is less than the maximum power. The efficiency is still poor, being of the order of 40% only, but it is sufficiently good to enable the sources of loss to be reasonably allocated and related to power output.

Thus at maximum power output, the input power per phase was distributed as follows:

	watts
Power input	52·2
Mechanical output	20·9
(including friction and windage)	
Balance	31·3

Of the 31·3 lost, 21 watts were lost in the stator copper.

It may also be deduced that stator leakage and magnetizing current are much too high. Bearing in mind that the larger a machine is made the easier it becomes to obtain good values for stator copper loss, magnetizing current and leakage, these results were thought to be encouraging and to indicate that there was no serious loss due to the stator array end-effects referred to in Section 3. The broken curves in Fig. 13 show similar results with the stators turned through about 40° to give a 30% increase in speed. The torque and input-power curves are seen to be similar in form, and the maximum power output and maximum efficiency are not noticeably reduced, but they occur at higher speeds, as expected. When, with the machine running light, the stators were smartly returned to the $\theta = 0$ position, the wattmeter reversed, indicating regenerative braking and illustrating the possibility of variable-speed induction generation.

The final set of experiments was concerned with pole end-effects and array end-effects. First one set of coils was disconnected on

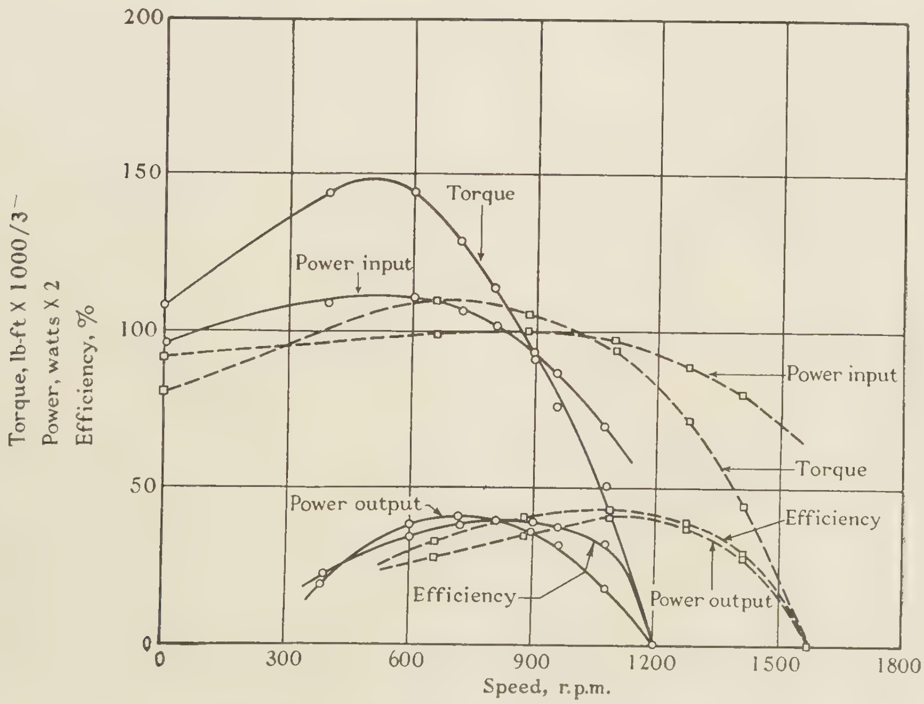

Fig. 13.—Performance curves of the experimental machine.

each stator (see Fig. 9), leaving only coils 1, 2 and 3 operative. If array length was important this should have reduced the speed range: it did not. Next, stators were made up as shown in Fig. 9, giving p/w values of $\frac{1}{2}$, $\frac{1}{4}$ and $\frac{1}{8}$. The speed range was checked for each set, and the results are shown by the numbered circles 1, 2 and 3 in Fig. 8. Agreement is good for the first two but poor for the third. This is not surprising, since the last set had a pole pitch smaller than the rivet spacing in the rotor and the winding was not spread. Furthermore, at the maximum speed the inner edge of the stator was aimed straight at the centre of the disc.

(6) COMMENTS AND CONCLUSIONS

The paper is intended purely as an early statement of an observed effect that is believed to be novel, and it would be inappropriate to discuss at length its possible practical applications until more information is available about efficiency, construction costs, maximum speed range and so on. The main conclusion is therefore that the effect exists and that its characteristics are at least qualitatively understood. The secondary conclusion is that further exploration of associated phenomena and their possible utility is worth while, and this is proceeding.

Since it is possible to make a variable-speed induction motor using the effect, and since it has been shown that such a machine can also be used as an induction generator, presumably all the properties of the normal squirrel-cage induction machine have their equivalent in the new machine. It has been found, for example, that given a start the machine will operate on single phase and still exhibit variable-speed properties.

In the case of the disc machine it may be noted that the speed achieved is independent of the sign of θ; thus with a pair of stators, one on each side of the disc, it is permissible to turn one clockwise and the other anticlockwise, so that the travelling fields have an angle 2θ between them, instead of remaining parallel (see Fig. 14 for $\theta = 45°$). The resultant of these two travelling fields is a chequer-board pattern, as shown in Fig. 14,

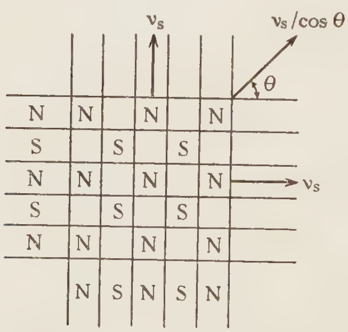

Fig. 14.—Effect of two fields moving in different directions.

travelling along the bisector of the angle at velocity $v_s/\cos\theta$. This mode of operation has the advantage that the force remains directed tangentially, but the eddy paths are different and the resulting torque is less than when the fields are maintained parallel.

The disadvantages of the disc machine have been outlined in Section 4, the main one being the change in surface speed with radius, which limits stator width, and this in turn limits pole pitch, since w/p must be large. Some easement of this restriction can be obtained by changing from disc construction to barrel construction, which, since it has been almost universally adopted in contemporary machines, must carry many other advantages also. In normal machines cylindrical barrels are used, but with these the stator poles cannot be rotated about the relevant axis withou[t] fouling the rotor. Spherical barrels are free from this defect, a[s] will be seen from Fig. 15, which shows a rotor and one set of stato[r] windings in position. A machine of this type is in course of con[-]struction, and it is expected that it will show much greater effi[-]ciency than the disc. For a given rotor radius a pole-width equa[l]

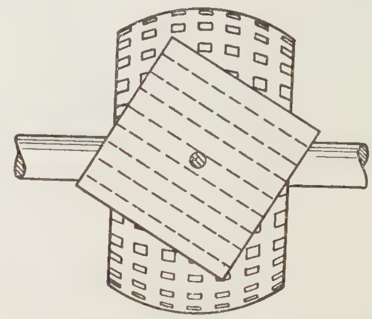

Fig. 15.—Arrangement of rotor and stator in a spherical machine.

to the radius can be employed with only a 12% variation of surface speed under the pole. Thus much bigger pole structures will be possible, resulting in lower stator copper loss and a bigger pole pitch with its attendant higher speed. Furthermore, the relative size of the gap will be less, so that leakage inductance will be reduced. With this machine it should be possible to form a better opinion as to the practicability of the device. It is amusing to note that with two stator assemblies set at different angles, one motoring and the other generating, it should be possible to do back-to-back tests on a single machine.

One other feature of this type of machine that may be of value is that by suitable arrangements the stators may be made self-adjusting for optimum effective gear ratio. This is most easily explained in the case of the disc machine, where it can be arranged that the line of thrust produced by the stator passes to one side of the axis of stator rotation, as shown in Fig. 16. Stator reaction

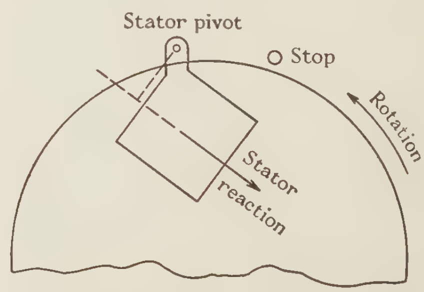

Fig. 16.—Disc machine arranged for optimum gear ratio.

will therefore drive the stator towards the low-speed high-torque condition. If the stator is driven away from this position towards the high-speed position by a spring, the stator angle will adjust itself to that position in which stator reaction and spring effect are equal and opposite. This condition will be a function of disc speed, and as the disc speeds up so the stator will rotate towards the high-speed position, maintaining acceleration under conditions of constant power as set by the spring tension. This property is not present in ordinary induction motors, where acceleration is a considerable function of slip, and where the input power varies widely during run up from, say, half speed to full speed.

(7) ACKNOWLEDGMENTS

The authors are indebted to Mr. Arthur Gledson for advice on mechanical design and for the construction and modification of the experimental models. They are also indebted to several members of the staff of the Department for helpful discussion and for mathematical help with the Appendix.

(8) APPENDIX*

(8.1) Calculation of Approximate Relative Size of Accelerating and Braking Forces

Referring to Fig. 17, a sheet of copper is constrained to move in the direction indicated at a speed v_q under a single pole N of length $p/2$ and width w.

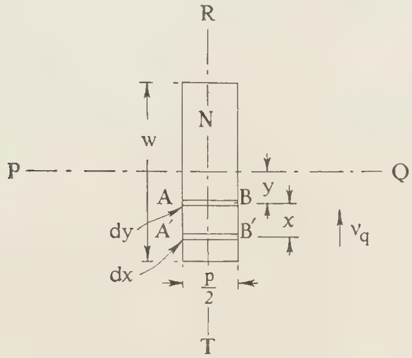

Fig. 17

Consider the strip AB of width dy at a distance y from the centre line PQ. The e.m.f. induced along this strip will be

$$V = \frac{pBv_q}{2}$$

Assuming that this e.m.f. is wholly expended in overcoming the resistance of the strip, a current $V\frac{2\sigma dy}{p} = \sigma B v_q dy$ will flow in the strip, where σ is the conductivity of the sheet at the thickness considered.

The braking force due to this current will be

$$f_1 = \frac{\sigma B^2 p v_q}{2} dy \quad . \quad . \quad . \quad . \quad . \quad . \quad (6)$$

The return path of this current will be distributed over the copper sheet. The current distribution will be assumed to be the same as that produced by a point current-source at one end of the strip and a point current-sink at the other, acting in a thin sheet.

The return current density J at any point on the centre-line RT distant x from AB will then be

$$J = \frac{\sigma B v_q}{\pi}\left[\frac{\frac{p}{4}}{\left(\frac{p}{4}\right)^2 + x^2}\right] dy$$

The return current flowing across the middle part of an element A′B′ of width dx is

$$J dx = dy \frac{\sigma B v_q}{4\pi}\left[\frac{p}{\left(\frac{p}{4}\right)^2 + x^2}\right] dx$$

and since the whole of this current must cross the pole, though not in a straight line, it will give rise to a driving force

$$df_2 = \frac{dy \sigma p B^2 v_q}{8\pi}\left[\frac{p}{\left(\frac{p}{4}\right)^2 + x^2}\right] dx$$

and the total driving force due to the return current from the element AB will be

$$f_2 = \frac{dy \sigma p B^2 v_q}{8\pi}\int_{y-(w/2)}^{y+(w/2)}\left[\frac{p}{\left(\frac{p}{4}\right)^2 + x^2}\right] dx$$

$$= \frac{\sigma p B^2 v_q}{2\pi}\left[\tan^{-1}\left(\frac{y + \frac{w}{2}}{\frac{p}{4}}\right) - \tan^{-1}\left(\frac{y - \frac{w}{2}}{\frac{p}{4}}\right)\right] dy \quad . \quad . \quad . \quad . \quad . \quad (7)$$

Using eqns. (6) and (7), the net braking force due to the element AB will therefore be

$$f_1 - f_2 = \frac{\sigma p B^2 v_q}{2\pi}\left[\pi - \tan^{-1}\left(\frac{4y + 2w}{p}\right) + \tan^{-1}\left(\frac{4y - 2w}{p}\right)\right] dy$$

and the total braking force will be

$$\int_{-w/2}^{+w/2}(f_1 - f_2) dy =$$

$$\frac{\sigma p B^2 v_q}{2\pi}\left\{\pi w - 2w \tan^{-1}\left(\frac{4w}{p}\right) + \frac{p}{4}\log\left[1 + \left(\frac{4w}{p}\right)^2\right]\right\}$$

This expression may be seen to consist of two parts:

(i) the braking force

$$F_1 = \frac{\sigma p B^2 v_q w}{2}$$

due to the forward current of the elements such as AB, and

(ii) the smaller driving force

$$F_2 = \frac{\sigma p B^2 v_q}{2\pi}\left\{2w \tan^{-1}\left(\frac{4w}{p}\right) - \frac{p}{4}\log\left[1 + \left(\frac{4w}{p}\right)^2\right]\right\}$$

due to the return currents.

In a practical case we do not have a single pole as in Fig. 17,

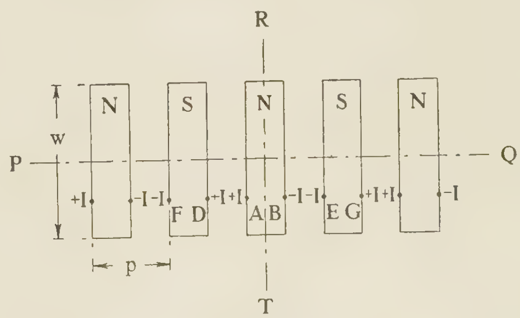

Fig. 18

* As a result of the discussion following the presentation of the paper in London, this Appendix has been entirely rewritten.

but an array of poles as in Fig. 18. The total force on the centre pole in this Figure will now be calculated. The forces due to currents initiated under the centre pole will be as for the previous case. Any one of the remaining poles can be split up into elements such as AB of Fig. 17, and each such element will give rise to a forward current and a return current. Some parts of the return currents will intersect the centre pole and give rise to forces on it. These return currents will once again be regarded as due to a current source and a current sink, and one set of such current sources and sinks is shown in the Figure. If now these sources and sinks are not taken in the pairs in which they originate, but in pairs symmetrical about the line RT, the equation previously calculated for the effect of return currents still applies, there being, of course, in this case, no contribution from the forward current. For example, for those such as the first pair D and E in the Figure, distant $3p/2$ apart, the force on the centre pole due to the return currents is

$$F_3 = \frac{\sigma p B^2 v_q}{2\pi}\left\{2w \tan^{-1}\left(\frac{4w}{3p}\right) - \frac{3p}{4}\log\left[1 + \left(\frac{4w}{3p}\right)^2\right]\right\}$$

and this is a driving force.

The current due to the second pair, F and G, distant $5p/2$ apart, is

$$F_4 = \frac{\sigma p B^2 v_q}{2\pi}\left\{2w \tan^{-1}\left(\frac{4w}{5p}\right) - \frac{5p}{4}\log\left[1 + \left(\frac{4w}{5p}\right)^2\right]\right\}$$

and this is a braking force.

The new dipoles must, of course, always be taken in pairs because the first pair cannot exist without the second. Additional poles introduced in pairs, one on each side of the centre, can be allowed for in a similar manner. Thus it is possible to evaluate the braking force F' on the centre pole for any given case in the form

$$F' = F_1 - F_2 - F_3 + F_4 + F_5 - F_6 - \ldots$$

This has been done for a number of practical cases and it is found that in all these cases

$$F' \simeq \frac{\sigma p^2 B^2 v_q}{8}$$

Thus the ratio of the driving force F as calculated in Section 3 and the braking force F' as above is seen to be

$$\frac{F}{F'} = \frac{4w}{p}\frac{v_r}{v_q}$$

DISCUSSION BEFORE THE UTILIZATION SECTION, 9TH DECEMBER, 1954

Prof. J. C. Prescott: The authors have introduced to us a new and most interesting form of induction motor. The theory of its operation can be stated briefly by saying that there will be no induced currents in the disc and therefore no driving torque if the linear velocity of the disc under the stator element has a component equal in magnitude to, and in the same direction as that of the advancing field produced by the polyphase currents. This condition of zero torque will define the synchronous speed. Thus, in Fig. A, if v_s represents the velocity of the field in magnitude and direction and OP the direction in which the disc is constrained to move under the stator element, then at synchronism the disc must have a component of velocity in the direction of v_s and equal in magnitude to it, such as v_s'. But the disc is moving along OP, so we must combine with v_s' a velocity v_q at right angles to v_s' to give the disc velocity v_c. This velocity will be greater than v_s if the angle θ is greater than zero. If a torque is to be produced there must be some slip and v_s' must fall below v_s for motor action, but v_c may still exceed v_s. The motoring torque is a function of $(v_s - v_s')$. The braking torque is shown by the authors to be proportional to v_q.

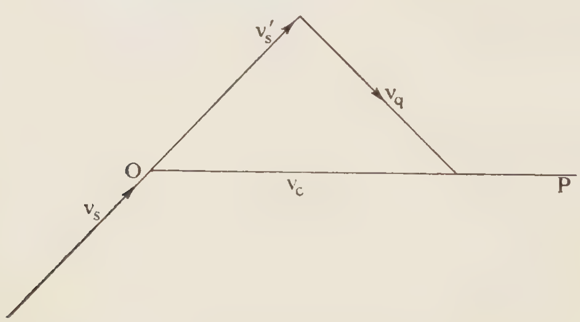

Fig. A

We see, then, that as the disc speed is increased by increasing the angle, the braking torque, which acts in such a direction as to oppose v_q, also increases and comes more nearly to oppose the disc velocity v_c; thus the power dissipated by this braking torque would appear to increase rapidly with increasing θ, and should cause a lowering of efficiency with an increase in synchronous speed. Fig. 13 does not show this effect, however. If I interpret it correctly, the full curve represents conditions where θ is zero and the braking torque zero also, while the dotted curves are appropriate to the case where $\theta = 40°$ and when a braking torque must exist. Yet the maximum efficiency is rather lower in the first case than it is in the second, and this would appear to require some explanation. It may be that the effect expected is masked by the high stator copper-loss, which is some 40% of the maximum power input, or that the impregnating iron rivets modify the disc currents which produce the braking torque.

Various opinions will be held as to the usefulness of the motor as a source of anything but small amounts of power. Even with the spherical rotor a frame size larger than that of a conventional induction motor would be required for a given output, and the mechanical difficulties arising in the construction of the machine would be considerable; not the last of these would be the provision of an adequate magnetic circuit. It is possible that these difficulties can be overcome; if they can, we should be able to obtain an induction motor with a wide range of speed control and good efficiency over the range.

Mr. G. B. Alvey: This new motor is of particular interest because the rotating member is, apparently, of robust and sound mechanical form and thus unlike most variable-speed motors which are complicated by insulated rotor windings and commutators or slip-rings.

Alternating-current commutator motors have become established for low and medium speeds, but in general, they are unsuited for the high speeds and high powers now required to drive large centrifugal pumps, turbo blowers, turbo compressors, etc. For such purposes motors at 3 000 r.p.m. up to about 5 000 h.p. capacity are now often required, and variable speed is sometimes an advantage. If this new motor could be developed for high-speed working, and for powers of this order, it would fulfil a real need, and I should like to ask the authors whether they think this is possible.

Another good use of this new motor would be where the atmosphere is contaminated with dirt and chemical fumes which are detrimental to the performance and reliability of the commutators and slip-rings of commutator motors.

Variable-speed squirrel-cage induction motors are now built in accordance with the principle established by Boucherot about 1894. By a suitable design of double-squirrel-cage rotor winding

an induction motor can be given a drooping torque/speed characteristic, i.e. at standstill the torque developed is a maximum falling away as the speed increases. Such a motor can have its speed varied by varying the voltage applied to the primary windings by an induction regulator or other device. These variable-speed squirrel-cage motors have characteristics similar to those of slip-ring machines which have their speed varied by external rotor rheostat. They have an unstable speed/load characteristic, which is sometimes a disability, and in this respect the new variable-speed squirrel-cage motor described by the authors appears to have an advantage.

Many variable-speed squirrel-cage induction motors operating on Boucherot principle have been supplied in recent years for driving high-speed centrifugal pumps, and for this duty the fact that the "slip" energy is wasted is not of great importance because usually the power absorbed by the pump falls very rapidly with reduction in speed. A typical instance is a 150 h.p. 4-pole motor operating from a 50 c/s supply driving a centrifugal pump. At the top speed of 1451 r.p.m., the power required is 148 h.p. and the efficiency is 90·6%. At a speed of 1350 r.p.m. the power required has fallen to 125 h.p. and the efficiency is 82·75%. At the lowest speed for which the equipment was designed, namely 1160 r.p.m., the power is 82 h.p. and the efficiency 71%.

If this new motor is to be a commercial success it will need to compete on the grounds of reliability, first cost and efficiency with existing types of variable-speed a.c. motors, including commutator motors and Boucherot-type squirrel-cage induction motors.

Prof. G. H. Rawcliffe: By turning the poles the authors have surely obtained the same effect as if they had moved them in and out along a radius. Conceivably it may be more convenient to turn the poles, but on the other hand you do inevitably introduce a braking effect. If you move them in and out you will have either no braking effect or a much smaller braking effect. In Fig. 4 the authors plot $r \cos \theta$ against time—I suppose it was really $r \cos \theta$ for a fixed r—but it would have been interesting to see what effect would have been obtained if the authors had chosen fixed values of $\cos \theta$, and changed r instead. I should like to know whether the authors have any experimental results for the comparative effects of reducing effective radius by turning and by lateral motion, because my impression is that reducing radius by lateral motion would be less liable to give a braking effect.

The authors have examined the consequences of the end-effects of the poles and of the array, but do not record the consequences of edge-effects in the disc itself. It would be interesting to have their comments on this.

I was slightly puzzled by the statement that w, the width of the poles, had to be limited, and that if w became too big something would go wrong. I take it that this simply means that the line of action will be directed on to the other side of the axis and will therefore give negative torque, but I should like to know whether there is anything more in the authors' minds, and whether broadening the width of the poles would have any other undesirable effect apart from directing part of the poles on to the wrong side of the pivot.

There are several obvious errors in the Appendix which call for correction, but—more important—I have not found the Appendix clear because the basis of the calculation is not explained. One cannot calculate the value of the effect which is shown in Fig. 6 except upon some assumptions. What are the assumptions behind the Appendix, and what is the basis of calculation?

There is also a misleading sentence in the Appendix which reads "For the accelerating-force considerations, the quantities d and w' are effectively interchanged . . ." If you effectively interchange them in F' you do not get F. It is clear that whilst the results are correct in the range over which the authors use them, they cannot be correct beyond that range. If $(p/w) = 2$ a square pole results, and F must be very nearly equal to F', whereas the Appendix would give $(F/F') = 2$. Therefore the lowest two curves in Fig. 7 must be somewhat hypothetical because that for $(p/w) = 2$ would plainly be wrong, since the pole would be square and F would be equal to F'. If the basis of the calculations in the Appendix were to be explained, and the errors corrected, something would be added, because the real novelty of the theory is the treatment of the ratio of F to F'.

I observe that in the latest form of the machine, there is one pole covering about a quarter of the periphery, and it seems to me that there would be no objection at all to putting four poles round the periphery, and more or less enclosing it. Have the authors the intention of putting more than two poles round the spherical rotor? It would be interesting to have a brief account of the construction of this "spherical" rotor and poles.

Whether the machine will have an industrial application is another matter, but if anybody can invent a variable-speed a.c. motor which has no wasteful losses and no sliding contacts, it will be the end of d.c. systems altogether and will completely revolutionize electric power drives. Therefore, although this machine is a long way from industrial application, I think nevertheless that a brushless variable-speed induction motor is a prize well worth chasing.

Dr. E. Friedlander: If the lines of the paper are followed up to the point where the authors derive first the forces F and F' in a primitive way, and if those equations are used rather than the more elaborate calculations of the Appendix, this leads to $\frac{4w}{p} = 1$ in eqn. (3), which, inserted into eqn. (5), gives just the eqn. (1) which has been found experimentally not to be valid. From this consideration it seems that the "edge" effect is essential for the motor to work as demonstrated. Without the greater difference in path resistance with respect to the two axes, the motor would slow down rather than speed up with increasing angle of displacement of the stator.

The authors hope that reduced leakage will help them. If the motor is visualized as being split up into two components, one being an ordinary motor which works at a low slip and the other one working on short-circuit, a different conclusion suggests itself —so far as the effect of leakage is concerned. The torque of a squirrel-cage motor which operates at low slip and high speed is little influenced by leakage, whereas the torque of a motor which works near its starting point is mainly limited by leakage. I should, therefore, not be surprised if the authors found that increasing the leakage in that axis which contributes to the braking torque must be very beneficial.

It is a pity the authors have not mentioned the motor built with a variable radius—which they thought would be too obvious to quote. It would have been interesting to compare both types. I have come across the problem of the motor with variable radius about twenty years ago when I was asked to investigate a 3-phase induction heater which was manufactured roughly along the lines of the stator used by the authors. In order to get rid of the forces which on that heater were detrimental, we had to reverse the phase sequence on half the conductors. This suggested that one could build a variable-speed induction motor by using a stator as explained by the authors and fitted with variable radius. The suggestion proved not to be new, since the existence of an earlier German patent specification was disclosed which illustrated precisely the same device. The design was not followed up at the time. Experimental verification on the lines

of the disc-rotor construction proposed by the authors may, however, still be worth while.

Mr. W. Hill: I think this is the first time that we have had a type of induction motor which gives an efficient method of speed control. There has been one other attempt, which was not really a type of variable-speed induction motor, to produce a variable-frequency supply, and that was achieved by means of an alternator employing a rotor within a rotor within a stator. It produced a very large machine which has never been used commercially.

The authors have produced the first type of variable-speed induction motor ever made. The original induction motor started as a disc machine about 70 years ago, so there is no way of saying how far this particular machine will go. If there is an application for an efficient machine to give an infinitely-variable speed function, the manufacturing industry will evolve an efficient and economic way of building it.

I would point out one requirement if this machine is to work at all. From Fig. A it will be seen that it is absolutely necessary for the current to flow in the direction of v_s. In the ordinary disc you always have a path in that direction for the current to flow, but in the induction motor the stator field and rotor field must have the same speed in space. If that does not occur you will not get any useful torques.

We have seen enough to suggest that this machine should have a name. The authors have anticipated me by saying that it is like a sailing craft skimming over a lake at a speed much faster than that of the wind itself. That, of course, is due to the so-called wedge action of the sail and keel, and it is felt that this machine might perhaps be called the "wedge machine."

One thing which I found a little difficult to follow is that the speed in Fig. 13 is 1 200r.p.m. when, by all the rules and regulations, it should be somewhere around 900r.p.m. In Fig. 10, the induced e.m.f. in the squirrel-cage motor will give some residual current with very little torque, but there is of course a position where it is true.

One point in which most designers of squirrel-cage machines are particularly interested are large harmonic dips in the speed/torque curve, and it might repay some investigation to ascertain whether or not there might be some harmonic dips which in a machine for high outputs would cause crawling and thereby make it useless. There is a big gap, in Fig. 13, of experimental data between the torques at about 400r.p.m. At the same time, slot harmonics which have a big influence in induction motors can be discouraged completely because there is another dimension in which to provide means of cancellation of the slot-opening effects.

Induction motors having between 30 and 80 poles will always mean large magnetizing current, but if variable speed is the effect that is required, all difficulties can be overcome and there will be a future for it.

Mr. O. I. Butler: It is somewhat surprising to hear of the recent upsurge of interest in "linear" 3-phase motors, in connection with the launching of aircraft. It may be of interest if I mention that the idea of "linear" 3-phase motors was being discussed in 1905.* It was called the "tangential traction system," and was patented in Belgium over 50 years ago. It used 40ft passenger coaches as the secondary of an induction motor, with the primary windings fitted to polar projections on the track at about 40ft intervals.

Everyone will agree with the desirability of using the normal cylindrical construction of induction motors. The extent of the ultimate application of the principle given in the paper appears to depend more on mechanical rather than electrical ingenuity, in solving an electro-mechanical problem. Evidently in order to obtain a change of speed, it is necessary that the motion of the secondary circuit shall be constrained to, say, one fixed direction, whilst the direction of motion of the primary field shall be adjusted to some other direction. Does this involve a complication in the use of the normal slotted-rotor construction, even with a spherical rotor, utilizing circular core plates? In this case, the flux in the vicinity of the conductors is constrained to the plane of the rotor, i.e. to a constant plane, irrespective of the movement of the stator system. However, there is still a "bending" of the flux in the air-gap and slots, and the effect of the core plates may be of secondary importance only, if of any consequence.

Is it not possible to commence with two sources of the primary field, having different directions of motion but with the actual field sources fixed in space? An effective change in the direction of motion of the resultant field is then achieved by weakening or strengthening one of the component fields. At first sight, it seems that the practical difficulties will prevent this being accomplished.

The new motor is similar to the shunt-wound d.c. motor, in so far as it gives speed increase at constant power above a rated minimum speed. The latter speed, for $\theta = 0$, appears to give optimum overall performance of the new motor. Evidently, the motor is subject to the difficulties of conventional induction motors so far as a decrease in speed below the optimum speed is concerned. However, the optimum speed is so low with a 50c/s supply that most practical applications will require an increase of speed. In this case, it appears that the torque/speed characteristics are such as to result in a decrease of the ratio of full-load to no-load speed, with consequent increased heating of the secondary circuit. Thus, it may be that the permissible percentage of speed increase is restricted by this consideration. Nevertheless, it is quite certain that the motor should be useful for many practical applications.

Dr. David Morris: I have had difficulty in appreciating the significance of the Appendix, partly in respect of the details of the analysis, but mainly because the study of the forces on an infinite conducting plane moving adjacent to an isolated pole appears to have little relationship to the more relevant idealized systems of Figs. 5 and 6. From a study of Fig. 5 (in which $p = \frac{1}{2}w$), once $p < \frac{1}{2}w$ any further increase of the number of poles in a given length might be expected to have very little effect upon the driving force, because the resistance offered to the circulating current consists mainly of the resistance of the path under the pole, and end effects are very small. From a study of Fig. 6 for a given area of pole system, the length of the current path in which e.m.f. is generated is proportional to p, whereas the resistance of the path is likely to be inversely proportional to p, because most of the resistance is in the transverse section between the poles, and decrease in the pole pitch would constrict this section. From these considerations it would

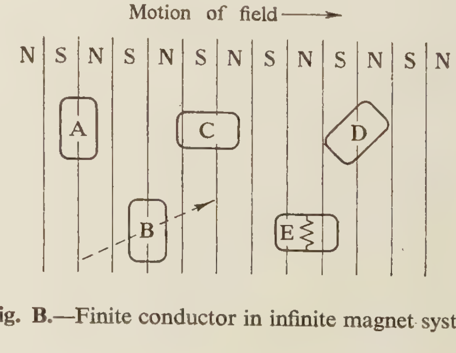

Fig. B.—Finite conductor in infinite magnet system.

* Wilson, H. W.: "Electrification of Railways," *Transactions of the Liverpool Engineering Society*, 1905.

appear that once p becomes less than $\frac{1}{2}w$, the factor relating the longitudinal driving force to the transverse braking force is likely to be proportional to $(w/p)^2$, rather than to the quantity (w/p) derived in the Appendix. Information concerning further tests would be valuable, because the reliable results quoted in the paper do not suffice to establish experimentally the index to be attributed to (w/p).

One of the most fundamental diagrams in the paper is Fig. 2, showing an infinite conducting plane moving adjacent to a finite magnet system. An interesting variant for consideration is a finite conductor moving adjacent to an infinite magnet system. Fig. B illustrates a particular case in which the finite conductor is a rectangular coil with sides equal to the pole pitch and to twice the pole pitch. In aspect A, the coil, if free to move, would travel at synchronous speed in a direction perpendicular to the pole edges. If constrained to move in the same aspect along the dotted line as at B, the speed along the dotted line would be greater than the above-mentioned synchronous speed. There is no transverse braking force. A variable-speed induction motor operating on torque control is possible if the aspect of the coil is made variable, as at A, C and D. Alternatively, high starting torque could be obtained as at E. For embodiment, the secondary coils would have to be placed in a spherically concave pole as used by the authors, with the supply connected to a wound rotor.

The authors' suggestion that their machine has all the desirable properties of the normal squirrel-cage motor is not true in one important respect. In main principle, an ordinary induction motor when running without restraint will have no loss in the rotor. Except when $\theta = 0$, there is no speed at which the machine as described by the authors will run without loss in the rotor.

THE AUTHORS' REPLY TO THE ABOVE DISCUSSION

Prof. F. C. Williams and **Mr. E. R. Laithwaite** (*in reply*): We are deeply indebted to the several contributors to the discussion who drew attention to the Appendix, for in process of reconsidering this we discovered in it a major error not exposed by the discussion. With the concurrence of The Institution the Appendix has been withdrawn and a substitute has been provided in the final version of the paper, and it is hoped that this will answer all the points related to the Appendix. The authors are also indebted to various contributors who have expanded and clarified the consideration of matters dealt with in the paper. Prof. Prescott's Fig. A, with the attendant discussion, provides a valuable addition, and we think he is almost certainly right. He predicts additional losses at angles other than $\theta = 0$. He is also almost certainly correct in assuming that it was the high stator copper loss and the elementary nature of the experiment as a whole that masked this effect in Fig. 13. Later experiments with different apparatus have shown that this effect does exist.

With regard to the Boucherot type of variable-speed motor discussed by Mr. Alvy, these are essentially variable-slip rather than variable-speed motors, and therefore necessarily have a limited speed range if efficiency is to be maintained at a high figure. The speed range he quotes in his example is a mere 20% reduction. We are aiming at a bigger range but must admit that efficiencies of the order he quoted for his Boucherot machine have not yet been obtained. It appears in the light of the experiments made so far, additional to those quoted in the paper, that efficiency will be improved as size is increased, and we therefore foresee no difficulty in manufacturing 5 000h.p. machines. It does, however, seem improbable that 3 000r.p.m. will be achieved at 50c/s. A more probable top speed is 1 000r.p.m., with a 3:1 reduction available below this. Even these figures may be optimistic.

We are unable to provide any information for Prof. Rawcliffe about the effect of variable radius. It has always been considered that the spherical arrangement is more promising, and the equivalent of variable radius in this case is extremely unattractive from a practical point of view. Our expectation that there would prove to be nothing new in the variable-radius arrangement is borne out by Dr. Freidlander's reference to a patent on the subject.

We have no comment at all to make about edge effects in the disc. It is, of course, expected that in any practical machine the available surface of the machine would be covered with stator pole sets.

Dr. Freidlander is almost certainly correct in his belief that increased rotor leakage will yield improved performance. Throughout the paper the leakage referred to is stator leakage, and it is reduction of this which we expect to lead to improved results. So far as stator leakage is concerned there can be no differentiation between the driving and braking phenomena since a single stator winding provides both effects and all that stator leakage can ever do is to provide a reduction of effective flux density on load. We therefore believe that we are proceeding correctly in attempting to reduce it. Rotor leakage was not referred to in the paper because the theory given relates essentially to resistive rotors, but we were already of the opinion that some rotor leakage would be beneficial, and, in fact, at the time the paper was read, preliminary experiments with the spherical machine had shown that results superior to those of Fig. 7 could be obtained by including rotor leakage.

Mr. Hill's suggestion that we should give the machine a name is under consideration. We think that in calculating the synchronous speed he has overlooked the fact that the effective radius of the stator is under 5in; 6in is the outside radius. It seems likely that the harmonic dips will be largely eliminated by the considerable skewing of the stator relative to the rotor. We are considerably encouraged by his optimistic attitude towards constructional difficulties. Our experiments show no evidence of any difficulty in rotor construction of the type envisaged by Mr. Butler. Our spherical machine uses the conventional core-plate construction and appears to operate as well as anticipated.

The effect of combining two travelling fields at an angle to each other is touched on in Section 6, and it would appear from this that any attempt to obtain variable speed by varying one of the field strengths could only result in speed control of a variable-slip kind. The effects of speed variation on efficiency and heating have yet to be examined.

Dr. Morris's "inversion" of the machine described in the paper is of considerable interest. Referring to his Figure, the speed variation obtained by the method summarized by A and B is essentially the method used in the paper, except that in his case the practical difficulties of terminating the field have not been considered. His cases (*c*), (*d*) and (*e*) obtain speed variation by slip control and are therefore necessarily inefficient. They correspond in this respect to the method of speed control which we demonstrated during the presentation of the paper, in which θ is varied about the 90° position and not away from zero. This also leads to a torque-control type of operation.

DISCUSSION ON
"THE TRANSIENT BEHAVIOUR OF LADDER NETWORKS OF THE TYPE REPRESENTING TRANSFORMER AND MACHINE WINDINGS"*

Dr. E. Friedlander (*communicated*): In his objection to the treatment of the transient behaviour of transformer windings by Rudenberg, the author assumes that the ladder network shown in Fig. 2 would give a true representation of a transformer winding. A cylinder winding or one layer of a multi-layer winding in a transformer is more akin to a smooth transmission line than to a ladder network because, in these windings, there is no distinct subdivision in a finite number of sections. A multi-layer winding cannot be reconciled with the author's assumptions anyway. Apart from the terminal turn of a cylinder winding, it is not possible to say where any turn begins or ends along the circumference, and the fact that adjacent turns are linked by a capacitance bridging a finite section of the winding does not convert the winding into a ladder network of the type shown in Fig. 2. However, the difference between the electrical behaviour of a ladder network and a transmission line is just that the ladder network is sensitive to a limited number of critical frequencies, whereas, also, any intermediate frequencies may be transmitted on the smooth transmission line. For proving the superiority of its own conception the author would first have to show that the ladder network he considers is a better representation of a transformer winding than the transmission-line type of network assumed by Rudenberg.

Dr. T. J. Lewis (*in reply*): Dr. Friedlander appears to misunderstand both the purpose of my paper and also the nature of my criticism of the work of Rudenberg.

The paper attempts to provide a general treatment of a class of network which, in several variations, has been used to obtain the surge behaviour of different types of equipment; the transformer being one such type. The basic element of the general network is shown in Fig. 2, and the several variations, to suit more closely particular cases, are considered under later headings in the paper. If Dr. Friedlander feels that a cylinder winding or one layer of a multi-layer winding is more akin to a smooth transmission line, the appropriate network is discussed in Section 7.2.2. (I am doubtful on this point, however, and suggest that Section 7.2.1 is more appropriate.) In fact eqn. (23) summarizes the conditions under which the subdivided network goes over to a continuous network without fundamental changes in network behaviour. This, in particular, was one point which the paper was intended to show. I cannot agree, therefore, with his statement that adjacent turns linked by a capacitance bridging a finite section do not convert the winding into the ladder network of Fig. 2.

Concerning the differences in the frequency spectrum of a subdivided ladder network and a transmission line, I cannot see his need to repeat these, since the differences are adequately stated in Sections 4.3 and 7.2.1.

In conclusion, Dr. Friedlander has seriously misinterpreted the relative merits of my treatment and that of Rudenberg. Both Rudenberg's treatment, as given in Reference 14, and the criticism offered in my paper, start from exactly the same equivalent circuit. The objections to Rudenberg's work do not concern the circuit representation but the subsequent mathematical treatment. Thus there can be no question of the relative merits of the two theories in the matter of circuit representation. As the title of the paper by Rudenberg indicates, a subdivided network is considered, and therefore both are of equal merit in representing a transformer winding. Dr. Friedlander's objection to the use of such a subdivided network is, in any case, immediately removed by reference to Section 7.2.

* LEWIS, T. J.: Paper No. 1691 S, October, 1954 (see **101**, Part II, p. 541).

DISCUSSION ON
"FLUORESCENT DISCHARGE-TUBE CIRCUITS AND OPERATING PROBLEMS"*
NORTH-WESTERN UTILIZATION GROUP AT MANCHESTER, 13TH OCTOBER, 1953

Mr. J. Martin: There are certain applications where the light from a tungsten-filament ballast lamp is required more for effect than efficiency, and it is an advantage in such applications to use an under-run ballast and thus eliminate the relatively large number of filament-lamp renewals required compared with tube renewals. By using a modified pre-heat quick-start circuit of the auto-transformer type, it is not only possible to use an under-run filament-lamp ballast, but, in addition, one of the normally expendable items—a starter switch—would also be eliminated. By this means the life of a tungsten-filament lamp is more or less brought into line with that of the fluorescent tube, and maintenance is therefore correspondingly reduced.

A typical example of this principle is the case of municipal illuminations, such as at Blackpool and Morecambe, where the narrow elongated shape of the tubes is particularly suited to the lighting of set pieces, etc., while the ballast lamps are used remote from the tubes to illuminate ancillary decorative effects such as individual artificial flower-heads, etc.

In view of the relatively short duration of these illuminations each year, the responsible authorities are much more concerned with the initial cost of the equipment than they are with the running costs, and the elimination of the choke and the capacitor, which are two of the most expensive components in the circuit, materially reduces the initial outlay.

Will the author explain why electrophoresis is apparent with the longer tubes yet absent in short tubes on d.c. operation, since it would appear logical to assume that the mercury vapour would migrate more quickly to the end of the tube when there is only a short length to travel as compared with the longer tubes?

* CATES, J.: Paper No. 1459 U, February, 1953 (see **100**, Part II, p. 389).

Users sometimes complain of early failures in fluorescent-lamp nstallations, and suggest more stringent factory tests. As a echnical executive of a leading manufacturer I can assure users hat our tests are very comprehensive; however, we have little control of the lamps during transit, and whatever mode of ransport is employed, there is always the unavoidable possibility of rough handling, and the dropping on one end of a carton of ubes may cause considerable damage, even though no visible breakages are apparent. When a carton of tubes receives a bump of this nature, almost certainly some of the filaments at that end vill either become dislodged or broken, or in many cases the ilaments become strained and distorted although not actually broken, and the weak spots thus created very soon become apparent by failure after the tube has been in use for a short ime.

Mr. F. Topham: The author has demonstrated the superior tability of the fluorescent lamp using capacitive ballast, but the nost popular ballast is inductive. Is there a sound reason for his? It has been shown that the cube-shaped choke is more efficient. If capacitive ballast were used, would it not be possible to design a rectangular condenser which would be nore easily accommodated in the lamp fitting, and not having he reduced efficiency experienced with a similar shaped choke?

When using two or more lamps so as to reduce stroboscopic licker, is it necessary to house all lamps in one fitting or can djacent fittings be used?

Mr. J. Tozer: A disadvantage of fluorescent lamps is the nnoying flicker which occurs when a fault develops or when a amp approaches the end of its life; it would be a great improvement if the lamp extinguished completely in the event of a failure n either the lamp or a component in the circuits. This is particularly annoying when several lamps are controlled from one witch. I have been concerned with the installation of a coninuous line of fluorescent lamps on either side of a turbine hall about 300 ft long. Although these lamps are controlled by instant-start switches, there is considerable flicker developing s the lamps approach the end of their life, and this spoils the ffect of what is otherwise a good installation.

The earthing of fluorescent fittings is becoming increasingly mportant as the circuits develop. It is quite common to find hat an earth terminal is provided on the tray on which the ontrol gear is mounted, but that the tray is fixed to the body of he fitting with only two 2 B.A. screws. The earthing of many nstallations relies on a satisfactory contact between the body f the fitting and the cable conduit, which ensures that the body f the fitting is earthed. It would seem imperative to ensure a reliable earth connection between the fitting body and the control gear, and I suggest that improvements are needed in this respect.

Mr. J. P. Heslop: When presenting the paper the author showed a slide indicating the variation of light output from a tube. However, the slide did not show any values of light output, and I wonder whether the test was taken with an uncoated tube. I would expect that the persistence of the phosphor powders would have given much more even light output than that shown.

The paper deals entirely with hot-cathode tubes. Have there been any developments in fluorescent tubes operating with cold cathodes for normal frequencies at the normal supply voltage?

In Section 2 the author deals with the various features of chokes and has stated that a British Standard is in preparation for this class of auxiliary equipment. The question of losses in cubic and elongated chokes has often arisen, particularly in connection with the computation of overall wattage of various sizes of lamp. While the British Standard is a manufacturing specification, it would prove of value to users of this type of equipment if the specification covered the losses of the various types and sizes of chokes.

Mr. F. Hollows: The probable cause of flicker is bad contacts. Within the last few days, while inspecting a new continuous-line installation, at the first switch-on I noticed flicker on a few tubes. When the fittings were examined the cause was found to be bad contact at the starter switch sockets. It is always advisable during installation to check the manufacturer's wiring connections, since contacts sometimes work loose owing to vibration in transit and installation.

Mr. G. H. Davidson: Does the author consider the instant-start circuit preferable to the starter-switch arrangement or vice versa?

The efficiency of the filament-lamp-ballast scheme is stated to compare favourably with normal tungsten-filament lighting, but the paper is really dealing with fluorescent-lamp circuits, and it is therefore the efficiency of the lamp-ballast scheme compared with the normal choke circuit which should be given. What are the overall efficiencies for these two schemes?

Regarding the operation of fluorescent lamps on supplies other than standard, what sizes of tube can be run from 110-volt single-phase supplies? Also, is it practicable to operate standard tubes on d.c. supplies in the 500–600 volt range, e.g. on traction or overhead-crane duties?

[The author's reply to the above discussion will be found overleaf.]

NORTHERN IRELAND CENTRE AT BELFAST, 12TH JANUARY, 1954

Mr. S. McCracken: I am surprised that the author should nake such favourable comment on the arrangement incororating a tungsten-filament ballast lamp, since the efficiency of his arrangement is only 25 lumens/watt compared with the 5 lumens/watt of the choke-ballast scheme. In fact, the tungstenlament ballast can be justified only on grounds of reduced first ost and the lighter weight of the unit. It must be emphasized, owever, that the reduced first cost will ultimately result in an xpenditure, for a given light output, very much in excess of hat which would have been incurred with the most conventional hoke ballast, owing to the increased consumption.

The author infers that the life of the tube will be seriously ffected by instant starting, but in view of the increase in life nnounced by the manufacturers since the paper was written, wonder whether he still holds the same views. The starter vitch has a much shorter life than the tube it controls; moreover, very time a starter switch gives trouble it reduces the life of the tube, so that the life of an instant-start tube should not be less than a switch-start tube, and it does have the inestimable advantage that it will continue to function throughout its life without trouble—and that cannot be said for the switch-start tube.

The author refers to the starting difficulties to be expected when operating under high relative humidity conditions. In this respect conditions could not possible be worse than those applying in a wet spinning room, and I have not experienced any particular starting difficulties under such conditions.

Surely the suggestion to coat the tube with a thin layer of silicone varnish could be looked upon only as a temporary expedient more applicable to laboratory than to industrial conditions.

I am surprised that the author has not made any reference to a simple resonant starting circuit consisting of a choke ballast with a capacitor and resistor connected in series across the lamp. It is appreciated that there are dangers associated with

such a circuit when used at normal power frequencies, but it has been used very successfully in transport lighting when operated at frequencies of the order of 400c/s.

Finally, I should like to comment that control gear to operate a fluorescent lamp apparently successfully can perhaps be made more cheaply than the majority of equipment associated with this industry, but tests may well show that the lower cost is achieved only at the expense of high equipment losses, reduced lamp life, reduced light output, reduced reliability or more probably a combination of all these defects. The importance of a really good-quality choke cannot be over-emphasized, since a choke in a fluorescent circuit will not permit of adequate protection by a fuse. Under fault conditions the current in the circuit will rise: in a choke-ballasted circuit with a 5ft lamp operated by a starter switch the current will rise from a normal value of 0·85amp to a fault current of, say, 1·3amp (actual tolerance 1–1·6amp). The higher current will, of course, result in increased heating of the choke, and since a faulty lamp is frequently left in circuit for some time, a choke is required which will withstand this increased heating for that period without breaking down or catching fire; however, the longer the period for which the choke design has to take care of the fault current, the more expensive the choke. What is a reasonable period for the choke to withstand such faulty conditions?

[The author's reply to the above discussion will be found below.]

NORTH MIDLAND UTILIZATION GROUP AT LEEDS, 13TH APRIL, 1954

Mr. W. Rule: The bulk of fluorescent tubes offered and used carry electrodes designed to be heated before the initiation of the discharge, and should be used in conjunction with control gear so designed that tubes will not start until the electrodes have reached a suitable temperature. Control gear which does not conform in this respect is marketed, and in some there is not even provision for the heating of both electrodes. Such control gear would have a markedly adverse effect on tube life.

The use of a $0 \cdot 005\mu F$ capacitor to connect the strip of an instant-start tube to neutral was not appreciably less effective than direct connection, but a high-value resistor would be equally effective and would reduce any possible shock hazard.

Mr. W. Waring: In Section 3.3 the author states that it is possible to use the same capacitor for all supply voltages over the range 200–250 volts by reducing the impedance of the series choke as the supply voltage is increased. In view of the wide manufacturing variations found with capacitors as compared with chokes, how may tolerance limits be satisfied for capacitive ballasts?

With reference to the method of power measurement in pre-heat instant-start circuits, it is my experience that the provision of filament heating reduces the cathode fall in the arc, with a resultant increase in the arc current; measurements made with no filament heating may therefore lead to incorrect results.

THE AUTHOR'S REPLY TO THE ABOVE DISCUSSIONS

Mr. J. Cates (*in reply*): In reply to Mr. Martin, the electrophoretic migration of the mercury in d.c. operation tends to be counteracted by the diffusion of the mercury vapour. If the ambient temperature (and consequently the mean mercury-vapour pressure) is sufficiently high, the effect of diffusion is great enough to avoid end darkening in short tubes where it would be still apparent in longer tubes.

As regards Mr. Topham's question on the capacitive ballast, the twin-tube arrangement has the advantages of lower cost, high overall power factor and reduced stroboscopic flicker as compared with shunt-corrected inductive circuits, and there is no sound reason for having all circuits inductive. Where only a single tube is installed, since the cost of the single capacitive ballast is greater than that of the inductive ballast, the latter would tend to be used. Where the twin-tube circuit is employed for adjacent single-tube fittings, the stroboscopic flicker will depend on how the light from the fittings is mixed.

Capacitors can be readily designed with the same cross-section as the choke; the capacitor losses are independent of the cross-section, but the cost is generally greater for an elongated type.

The annoying flicker which, as Mr. Tozer mentions, occurs in the switch-start circuit when a tube fails is much less apparent in the instant-start circuit. It is agreed that reliable earthing of the fitting is important.

The light output waveforms mentioned by Mr. Heslop are for coated tubes. There is an appreciable afterglow from the phosphor which results in a substantial light output at zero current during the cycle on a 50c/s supply; the ratio of minimum to maximum light during the cycle is about 0·4.

Brief mention of cold-cathode tubes and circuits has, in fact, been made in the paper. It is not possible to operate these tubes directly on low-voltage supplies without a substantial step-up in voltage.

The proposed British Standard does not specify limits for choke losses, but it does provide limits for choke-temperature rise.

In reply to Mr. Davidson, the instant-start circuit has the advantage of rapid starting and reduced maintenance as compared with switch start. As an example of the comparative efficiency of tungsten-filament-lamp and choke ballasts, the overall 100h efficiency for a 4ft 40-watt tube on a 230-volt 50c/s supply is 27 lumens/watt for the lamp ballast and 46 lumens/watt for the choke ballast.

The 18in 15-watt, 2ft 20-watt and 2ft 40-watt tubes can be operated directly on 110-volt supplies, while two standard 5ft 80-watt or a larger number of shorter tubes can be operated in series on 500–600-volt d.c. supplies.

In reply to Mr. McCracken, the tube life in a correctly designed pre-heat instant-start circuit is no less than in a switch-start circuit. Starting is reliable at high humidities on switch-starting, and also on instant starting when using an earthed metallic strip on the tube. With a more remotely connected starting wire the instant-start circuit is less reliable, but a coating of silicone varnish on the tube improves reliability considerably and this coating is quite practicable for service conditions.

I agree that the simple resonance circuit mentioned by Mr. McCracken is quite feasible for 400c/s supplies.

As regards the ability of the choke to withstand continuous starting conditions, the proposed British Standard does, in fact, specify a temperature limit for this condition.

With regard to the question of tolerance limits for capacitive ballasts, raised by Mr. Waring, the series capacitor can be manufactured to a tolerance of about $\pm 5\%$. This results in a tube power-consumption tolerance only a little greater than with a choke, but this increase is offset by the smaller variation of tube power with supply voltage in the capacitive circuit.

The method I have shown for tube power measurement in the instant-start circuit takes into account any alteration in arc current.

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Paper No. 1721 U
Oct. 1954

THE USE OF ELECTRICITY IN THE PRODUCTION OF CALCIUM CARBIDE

By C. J. BEAVIS, Member.

(*The paper was first received* 1*st February, in revised form* 8*th April, and in final form* 9*th June*, 1954. *It was published in October*, 1954, *and was read before the* SOUTH MIDLAND SUPPLY AND UTILIZATION GROUP 8*th November, and the* UTILIZATION SECTION 18*th November*, 1954.)

SUMMARY

The establishment of a carbide manufacturing industry in the United Kingdom has brought its own special problems for engineers and chemists to solve, and the object of the paper is to describe a typical factory deriving its electrical energy, which may be regarded as its principal raw material, from a thermal power station.

The paper outlines the history of the carbide industry from the discovery of acetylene in 1836 until commercial production commenced in 1892, with some notes on the various investigations carried out in the intervening period.

The development of the manufacturing process follows, from the early ingot or batch furnaces to the modern, for the production of "run" or "tapped" carbide, with a consideration of the chemical reactions involved.

A typical modern process is then described in some detail. It is based on a factory which was built in the United Kingdom by the Ministry of Supply. The plant requirements for self-sufficiency are noted from the preparation of the raw materials, other than electricity, to the dispatch of the finished product. Some notes on furnace design are also given.

The electrical distribution system is fully described, particular reference being made to those features which are considered to be peculiar to the industry.

Some particulars are also given of the various other services provided in the factory, such as road and rail transport, workshops and special provisions including some made in connection with safety precautions peculiar to the industry.

(1) INTRODUCTION

Acetylene was first observed in 1836 by Edmund Davy, some 60 years before calcium carbide was produced commercially. He had been heating a mixture of calcined tartar and charcoal to obtain potassium, and he produced a black substance (potassium carbide) which reacted violently with water to form a gas which burnt with a flame of extreme brilliance. It was little realized then that this gas would be the raw material of a large chemical industry for the synthesis of solvents and plastics of the p.v.c. group and of inestimable value in the engineering world.

During the next 50 years or so, this gas was produced in various chemical reactions and, in 1860, Berthelot published the results of his researches on the gas and gave to it the name "acetylene" and the formula C_2H_2.

It was Sir Humphry Davy who first demonstrated the possibilities of the electric arc, and between 1870 and 1890 various patents in respect of arc furnaces were taken out, chiefly concerned with the reduction of the oxides of various elements in the presence of carbon.

The next most important year in the history of the industry was 1892, when a Canadian, T. L. Willson, attempted to reduce lime by carbon and produced a hard crystalline substance which crumbled on exposure to air, and reacted violently when brought into contact with water, with the evolution of a gas which was identified as acetylene. This substance was shown to be calcium carbide. At about the same period, other workers were endeavouring to produce metallic carbides, and there has been some controversy as to whether Willson or a Frenchman, Moissan, was the first to produce calcium carbide commercially. There were also other claimants for this honour.

However, it now seems to be quite clear that it is to Willson that the credit must be given of first producing calcium carbide on a commercial scale in 1892 in an electric furnace.

After 1892, much research work was carried out on the chemistry of the production of calcium carbide in an electric furnace.

The generally accepted equation, namely

$$CaO + 3C + \text{heat} \rightleftarrows CaC_2 + CO$$

expresses a possible method of formation, but it is now thought that this takes place in two distinct phases.

The temperature of the electric arc is usually assumed to be of the order of 4 000° C, and it can be shown that the above equation is reversible at about 2 500° C. It is therefore evident that carbide cannot exist in the "hot zone" and that all the compounds are dissociated into their elements in the arc.

It is now thought that within the arc zone there exists only free calcium, gaseous carbon and oxygen, which on passing to a cooler zone combine to form carbide and carbon monoxide. The following equations probably represent more accurately the reactions in the furnace:

$$\text{(i)}\quad 2CaO + 6C\,(\text{solid}) + \text{heat} = 2Ca + O_2 + 6C\,(\text{gaseous})$$

$$\text{(ii)}\quad 2Ca + 6C + O_2 \rightleftarrows 2CaC_2 + 2CO$$

The early carbide furnaces were of the batch or ingot type, in which a mixture of lime and carbon, in the form of metallurgical coke, were pulverized, intimately mixed and placed in a refractory lined crucible, in which were two electrodes. A current was passed through the mass until the reaction was complete, when the electrodes were withdrawn and the mass allowed to cool. The ingot was then dug out and broken up and crushed into suitable sizes for the acetylene generators. Fig. 1 shows a representative type of ingot furnace in use at this time.

Many patents for ingot furnaces were taken out, but one of the most convenient types seems to have comprised a brick oven with a flue and support for raising and lowering the top electrode. An iron car, on the floor of which was a layer of carbon connected by a flexible lead to the other side of the electricity supply, was filled with the mixture of lime and coke and run into the oven. The top electrode was then lowered into the mixture and the current switched on. After the reaction was completed, the car was hauled out of the oven and the contents allowed to cool, after which the ingot was removed from the car and prepared for the market by crushing and screening. This type of furnace was developed by T. L. Willson.

Other types of ingot furnaces were used having different electrode arrangements, some with side-by-side and some with horizontal electrodes. It was considered by many that a furnace with top and bottom electrodes was more economical and produced better carbide than other types, but it had disadvantages, the chief one being a tendency for the impurities in the raw materials

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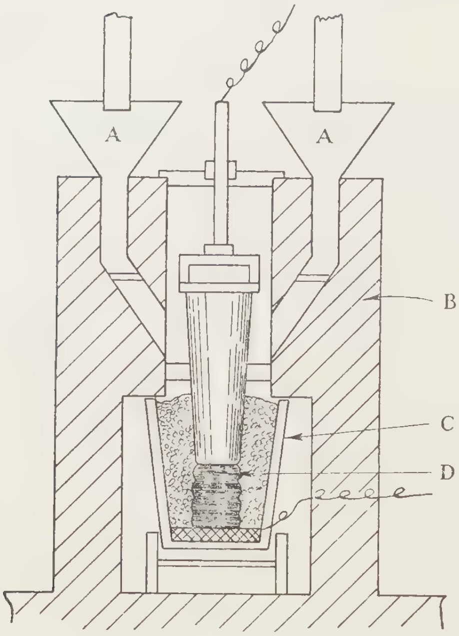

Fig. 1.—Ingot furnace.

AA—Raw-material chutes.
B—Brick oven.
C—Car containing lime–coke mixture.
D—Carbide ingot.

to fall to the bottom of the furnace and mask the lower electrode.

In general, it may be said that the disadvantages of ingot furnaces were soon appreciated, and a furnace for producing "run" or "tapped" carbide was evolved, and all modern processes now use furnaces of this type. The tapping is started by using an electric tapping "gun," and the first patent for this was taken out by T. L. Willson in 1906.

Calcium carbide was first manufactured commercially in this country in 1897, at Foyers in the north of Scotland, using furnaces of the Willson type, electricity being supplied from a hydro-electric station which was built nearby. Earlier—in 1895—an experimental plant had been built in Leeds from which a certain amount of carbide had been produced. Since 1900 work has been going on continuously in the development and improvement of electric furnaces for the production of calcium carbide, and the subsequent sections of the paper deal with a typical modern carbide factory.

(2) THE MODERN PROCESS

The manufacture of calcium carbide is essentially a smelting operation in which calcium oxide reacts with carbon to form calcium carbide with the evolution of carbon monoxide.

The temperature required for calcium carbide manufacture lies between 1 600 and 2 500° C, and this can most conveniently be obtained in an electric-arc furnace where the arc is submerged in the charge material. A furnace of this type is generally known as a submerged-arc furnace. Nowadays 3-phase furnaces, with the electrodes arranged in a triangle for reasons of electrical symmetry, are used.

The carbon required for calcium carbide manufacture is normally supplied in the form of coke, and the process requires a coke which is low in ash, sulphur and phosphorus. The oxides of silica and iron are reduced in the furnace to the metals and form ferro-silicon which is very troublesome in furnace operations, if present in excessive quantities. Sulphur and phosphorus pass into the product and cause impurities in the acetylene. For similar reasons, only a very pure lime can be tolerated in the furnace and a typical analysis of a suitable limestone is given below:

Silica:	Not more than 1·0%
Phosphorus:	Not more than 0·03%
Total impurities:	Not more than 3·0%

The reaction of calcium carbide and water is expressed by the equation:

$$CaC_2 + H_2O = C_2H_2 + CaO$$

and, from a consideration of the molecular weights, it can be shown that the gas yield of pure carbide is 5·86ft^3/lb at s.t.p. In normal operations it is not economical to produce pure calcium carbide, since the energy consumption would be too high. Carbide produced to B.S. 642 is approximately an 80% carbide/lime solution with a gas yield of 4·80ft^3/lb.

The theoretical energy requirements for pure calcium carbide can be deduced by calculating the energy necessary to dissociate the lime, plus the heat of formation of calcium carbide less the heat produced by the formation of carbon monoxide. To this must be added the sensible heat in the carbide as produced at 2 500° C: in this calculation the mean specific heat of calcium carbide is taken as 0·3:

	kcal/gramme-molecule
Heat of dissociation of lime	132·0
Heat of formation of calcium carbide	0·65
	132·65
Less heat of formation of carbon monoxide ..	29·00
	103·65
Plus sensible heat in calcium carbide	48·00
	151·65

Thus, the total heat for 64 grammes of calcium carbide is 151·65 kcal, and the total heat for 1 ton of pure calcium carbide is 2 400 000 kcal, i.e. 2 790 kWh.

The above calculations take no account of the heat losses from the furnace shell by radiation and that lost in the stack gases. It may be added that the energy rate of most commercially operated furnaces lies between 3 000 and 3 500 kWh per ton of 80% calcium carbide. A number of factors, however, can adversely affect this consumption.

In a furnace operating at a temperature suitable for the production of carbide, all heat losses are a function of time. Therefore, the greater the rate of heat input, the greater should be the rate of production of calcium carbide, with a consequent lowering of the energy requirements per ton of carbide made. This assumes, of course, that the carbide is removed from the reaction zone as soon as possible after its formation. In other words, the above statement holds good only if the furnace is successfully and completely tapped of its product for, if this be not so, not only is the rate of throughput diminished, but "stewing" of the calcium carbide causes its dissociation into lime and carbon, with subsequent deterioration in the quality and gas yield of the product.

It therefore follows that, in common with the majority of the other melting processes, the rate of heat input—in the case of a calcium carbide furnace, the electrical load—should be as high as the furnace design will permit, this in turn being governed by electrical capacity and furnace crucible dimensions, etc. This upper limit generally manifests itself, if approached too closely, by the high incidence of breakdowns in the internal water-cooled parts of the furnace, and break-outs of molten material through the furnace shell, as the area of the arc zone naturally increases in proportion to the power input; scouring and fusing of the brickwork increases and eventually exposes the shell which is burnt away. In Section 3, a method of calculating the hearth size is

described with particular reference to the area of the arc zones around each electrode.

(3) NOTES ON FURNACE DESIGN

Fundamentally, an electric-arc furnace with its low-voltage busbar and electrode assembly is equivalent to a circuit consisting of a reactance which, for practical purposes, is constant, and a variable resistor. The reactance is governed by the characteristics of the transformer and busbar/electrode assembly, as the furnace itself is considered to be non-inductive. The resistance consists of the materials of the charge in the furnace crucible.

The design must therefore start with a consideration of the required power input to the furnace. Sufficient practical knowledge is available for the energy rate of calcium carbide production to be taken as 3 500 kWh per ton (Section 2). A reasonable annual load-factor is 75%, and thus,

$$\text{Load} = \frac{\text{Annual production in tons} \times 3\,500 \times 100}{75 \times 8\,760}\ \text{kW}$$

The load thus calculated is then divided into as many operating units as may be considered desirable by the designer, in order to define the capacity of each furnace.

The next stage is to determine the electrode diameter, current and transformer voltage. Andreae[5] has shown that

$$D^3 = b^2 I^2$$

or

$$I = D^{\frac{3}{2}}/b$$

where D is the electrode diameter in inches, I is the electrode current in amperes and b is a constant calculated from the coefficient of heat transfer from the electrode to the atmosphere, the electrode temperature above the charge and the resistivity of the electrode material. This equation derives from the fact that the heat dissipated from the electrode in the area between the furnace charge and the contact shoes is equal to the I^2R loss in this part of the electrode.

Andreae has also shown that, for different sizes of furnace making the same product from the same raw materials, the resistance at the electrode tips multiplied by the periphery of the electrode is constant. This has been called the "peripheral ohm factor" and may be expressed as follows:

$$R\pi D = \text{constant}$$

or

$$R = C/\pi D.$$

Then, if V is the "in-phase" voltage to the furnace neutral, I the electrode current and P the phase power in watts,

$$V = IR = \frac{D^{\frac{3}{2}}C}{\pi b D} = \frac{D^{\frac{1}{2}}C}{\pi b}\ \text{volts}$$

and

$$P = I^2R = \frac{D^3C}{\pi b^2 D} = \frac{D^2C}{\pi b^2}\ \text{watts}$$

or

$$P_3 = \frac{3CD^2}{\pi b^2\, 1\,000}\ \text{kilowatts for a 3-phase furnace}$$

and thus,

$$D = \left(\frac{P_3 \pi b^2 \times 1\,000}{3C}\right)^{\frac{1}{2}}\ \text{inches}$$

There is, again, enough available operating data of calcium-carbide furnaces for a power factor to be decided at this stage.

A figure of 0·85–0·87 is usually taken. The "total-phase" voltage of the low-voltage circuit is then determined as

$$V_{ph} = \frac{V}{\cos\phi}$$

and thus, l.v. line voltage $= \dfrac{\sqrt{3}V}{\cos\phi}$

The electrode current, I, is then calculated from the formula

$$I = D^{3/2}/b\ \text{amperes}$$

The active area surrounding each electrode is generally assumed to lie within a circle of radius equal to the electrode diameter and to be concentric with it. A triangular spacing is generally preferred to an in-line arrangement of the electrodes, as the busbar reactance can be balanced more evenly. The three electrodes are therefore spaced at the apices of an equilateral triangle of such a size that the active areas of each just overlap.

The bowl can then be designed around the three electrodes with a refractory lining of such a thickness that, ideally, the annual value of interest and depreciation, plus the cost of maintenance and heat losses, is at a minimum.

The data for the specification of the busbar assembly and transformer is now determined from

$$R = \frac{\text{Peripheral ohm factor}}{\pi D}\ \text{ohms per phase}$$

and thus reactance $X = R \tan\phi$ per phase.

This value of X is the total reactance of the transformer and busbar assembly. The busbars are designed with a cross-sectional area to suit the electrode current and are arranged so that the difference between their reactance and the total circuit reactance is a value which the transformer designer can achieve in his design.

The general principles for the design of circuits of low reactance are well known and the most important of these are listed below:

(*a*) Circuits carrying current in one direction should be placed as close as possible to parallel circuits carrying the same currents in the opposite direction.

(*b*) No magnetic material should be placed in the vicinity of any of the circuits.

(*c*) All circuits should be as short as possible.

As shown above, the approximate value of transformer reactance has already been determined and, in general, it has been found that the transformers should have a percentage reactance of less than 2%.

For 3-phase transformer banks the connections are generally arranged in delta/delta, the low-voltage connection being made at the contact shoes on the electrodes. For purposes of load control, a number of taps above and below the calculated voltage are provided on the high-voltage side of the transformer.

The results of the formulae shown earlier in this Section have been determined for various sizes of furnace and are shown graphically in Fig. 2, from which the electrode diameter and spacing can be determined for a furnace of any given capacity, and Fig. 3, which shows the charge resistance against design load for various currents and voltages.

In Section 4.4 a description is given of a furnace, the size of which has been calculated on the basis of the data and curves given in this Section.

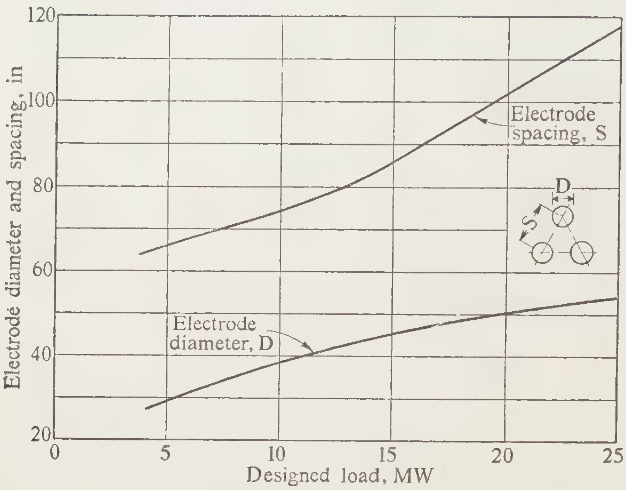

Fig. 2.—Electrode diameter and spacing plotted against designed load for 3-phase carbide furnaces.

(4.1) Quarry and Lime Plant

In Section 2 the necessity of a very pure lime was emphasized, and it is therefore essential that the quarry be situated where ample supplies of limestone complying with the specification given in that Section are available. The quarry output can be determined on the basis that every ton of carbide requires approximately 2 tons of clean graded limestone. The normal items of quarry equipment comprising rock drills, mechanical shovels, crushers, screens and conveyors are required.

For the production of the graded lime, which is required in carbide furnaces, modern practice generally favours the use of rotary lime kilns, mainly for the reason that they are suitable for a wide range of fuels and gradings of stone without modification.

The unit used comprises a refractory-lined steel cylinder about 200ft long and of 7ft 6in diameter inside the refractory lining. It has an enlarged zone of 9ft diameter inside the lining at the firing end. It is supported on roller beds at a slope of 1 in 25 towards the firing end and driven through suitable gearing at speeds varying from 0·5–1 r.p.m.

The kiln is equipped with a cooler through which the lime is

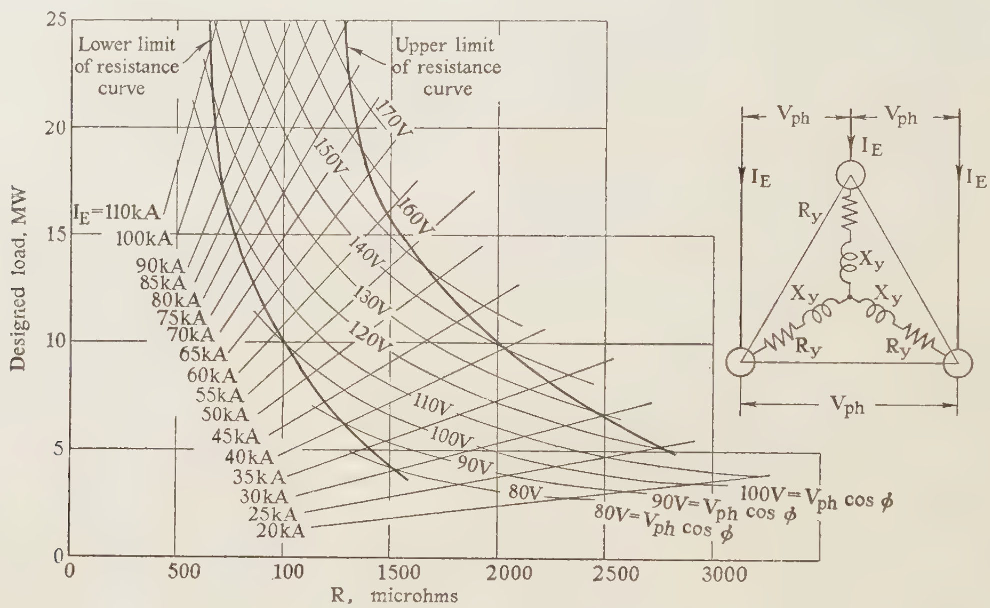

Fig. 3.—Designed load plotted against charge resistance for constant electrode currents and constant electrode voltages for 3-phase carbide furnaces.

(4) THE COMPLETE CARBIDE FACTORY

The choice of a suitable site for a carbide factory is largely dependent on the cost of electric power at that site, but the availability of other raw materials such as limestone for the manufacture of the lime, coking coal for the carbide process and anthracite for the electrode carbon, and steel for the manufacture of the drums in which the carbide is packed, plus an adequate supply of cooling water and transport, are important factors.

A modern carbide plant which is to be self-sufficient (except for electricity supply) requires the following:

- Limestone quarry.
- Lime burning plant.
- Coke preparation plant.
- Electrode carbon plant.
- Carbide furnace plant.
- Carbide crushing, screening and packing plant.
- Drum manufacturing plant.
- General services.

passed, which serves the dual purpose of recovering heat from the lime by giving it up to the air required for combustion of the fuel and, at the same time, reducing the lime to such a temperature that it can be conveniently handled by a conveyor of a normal type.

The kiln is fired with pulverized bituminous coal of such a fineness that 80% will pass a 200-mesh screen. The temperature in the burning zone of the kiln is between 1 300 and 1 400° C.

In order to draw the hot gases through the kiln, an induced-draught fan is installed at the back end of the kiln and, so as to recover some of the heat which would otherwise be wasted, the gases are passed through a preheater which serves to raise the temperature of the limestone up to approximately 500° C before it enters the kiln.

The cold lime is passed over a screen which rejects all material below $\frac{1}{8}$in, since this causes disturbances in furnace operations. The remainder is then elevated by a skip hoist to the main lime storage bunker. The hoist is fitted with electronic control gear,

designed so that the bucket will be hoisted only when it has been filled to the predetermined level. The metal "probe" for this equipment is set in the feed chute (from which it is insulated) to the bucket in such a manner that the electrical characteristics of a high-frequency oscillating circuit are varied when the chute fills up with lime above the "probe." This variation is used to cause the hoist control relays to be operated through thyratron valves.

The kiln unit described above would have an output of about 6·5–7 tons of lime per hour.

(4.2) Coke Preparation Plant

All the coke as received, except where it is graded to the correct size range, is passed through primary and secondary crushers where it is reduced to 1½–2 in maximum size. It is then elevated to bunkers commanding the coke-drying units.

The original form of drier consists of a steel cylinder about 30 ft long and 5 ft in diameter, through which hot gases from a coke-fired furnace are drawn against the direction of flow of coke. The cylinder is rotated at about 4 r.p.m. and is fitted with lifters to assist the drying.

This type of drier has now been superseded by a unit of thc static type in which hot gases are drawn through a mass of coke, contained in a refractory-lined cylinder fitted with baffles. The output of this form of drier is varied by a vibratory feeder which controls the rate at which coke is extracted from it. The main requirement of the driers is that they should be capable of delivering a coke with a moisture content not greater than 2%.

From the driers, the coke is carried by conveyor to the main coke bunker in the carbide furnace building, all material below ⅛ in in size being removed by screening for the same reason that the lime fines are removed.

(4.3) Electrode Carbon Plant

Although the early carbide furnaces used what in these days vould be called prefabricated carbon electrodes, the modern unit ıses a Soderberg self-baking electrode. For this a carbon paste s required which is prepared from calcined anthracite coal ınd a bond made up from a mixture of tar and pitch. The proportions of this paste are 80% anthracite and 20% bond.

Anthracite coal, as received at the factory in a mixture of grain ınd pea sizes, is a poor conductor of electricity. Before it can be ısed for the manufacture of electrode paste the resistivity must e reduced by driving off the volatiles in the calcining furnace. This furnace is electrically heated and comprises a vertical steel cylinder, refractory lined, with one electrode suitably suspended ıt the top and the other at the bottom of the shell. These electrodes are supplied by a 500 kVA 11 kV/75 volt transformer, onnected in open delta on both sides. Off-load tap changing rovides eight voltages from 75 to 55 volts for purposes of urnace control. The normal load of the furnace is about 50 kW. The transformer is of the core type with a reactance of pproximately 4%.

"Green" anthracite is fed in at the top of the furnace and the oal passes slowly through the cylinder, during which time the olatiles are driven off by the heat of the arc. The coal drops on ɔ a water-cooled circular plate just below the bottom of the hell. From this it is removed by scrapers and paddles in a vater-cooled ring at the edge of the plate. Fig. 4 shows a ypical arrangement of the furnace.

The normal operating voltage is 70–75 volts. The furnace is utomatically controlled by a current relay. As the coal is calned, the current passing through the furnace rises until a value f 4 000–4 500 amp is reached, at which the coal is considered be calcined. The relay then operates and switches on the raper/paddle motor, thus removing some coal and allowing esh to be admitted at the top; the cycle repeats itself after the

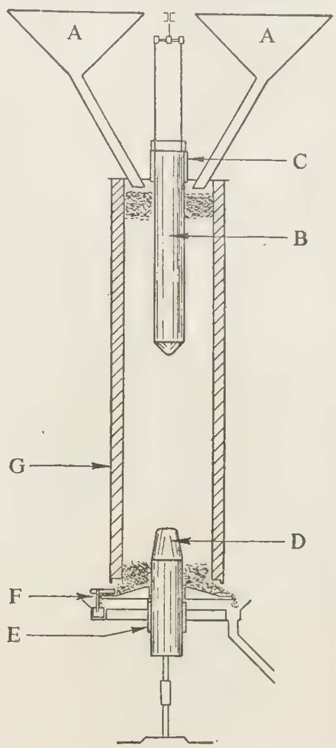

Fig. 4.—Anthracite calcining furnace.

AA—Anthracite chutes.
B—Top electrode.
C—Electrode clamp and busbar connection.
D—Bottom electrode.
E—Electrode clamp.
F—Calcined coal extraction gear.
G—Steel shell, refractory lined.

current has again risen to the predetermined value. The resistivity of the coal is laboratory checked and the relay set to maintain a value of 800–900 ohms/m/mm^2.

The calcined coal is then passed over a 10-mesh screen. All material below 10 mesh is passed into one bunker and all material over into another. Some of the larger of these two fractions is ground in a ball mill to pass a 200-mesh screen and is then delivered into a third bunker. In order to obtain mechanical strenght in the carbide furnace electrode, suitable quantities of the three grades of calcined coal are batch-weighed into a mixer and the correct quantity of bond added. The mixer body is maintained at a temperature of 100–120° C by the circulation of oil from an electrically heated and thermostatically controlled boiler.

After mixing for a period of 45 min the paste is transferred in trays to the paste floor of the carbide furnace building where it is fed into the top of the electrodes as required.

(4.4) Carbide Furnace Plant

The carbide furnace consists of an irregular 6-sided steel bowl with its sides sloping outwards from the base at an angle of about 70°, as shown in Figs. 5A and 5B. The bowl is refractory lined, the sides being 13 in thick and the base 6 in. At the commencement of the life of a bowl, a 5 ft bed of anthracite coal, ¼ in to dust, is placed in the bottom and well tamped down.

Figs. 5A and 5B depict the general arrangement of the carbide furnace. It will be seen that the taphole, A, is situated approximately in the centre of the short face of the bowl. This face is not of steel, but is constructed of refractory brickwork some 32 in thick. From top to bottom of the bowl, at each side of this

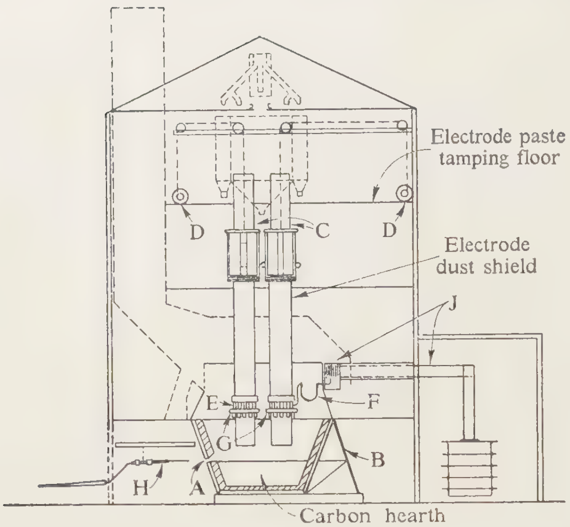

Fig. 5A.—Diagrammatic part elevation illustrating some features of symmetrical 3-phase carbide furnace using Soderberg electrodes.

A—Taphole.
B—"A" frames.
C—Soderberg electrodes.
D—Electrode winches.
E—Contact shoes.
F—Water-cooled conductors.
G—Clamp ring.
H—Tapping-gun assembly.
J—Interleaved busbar stack.

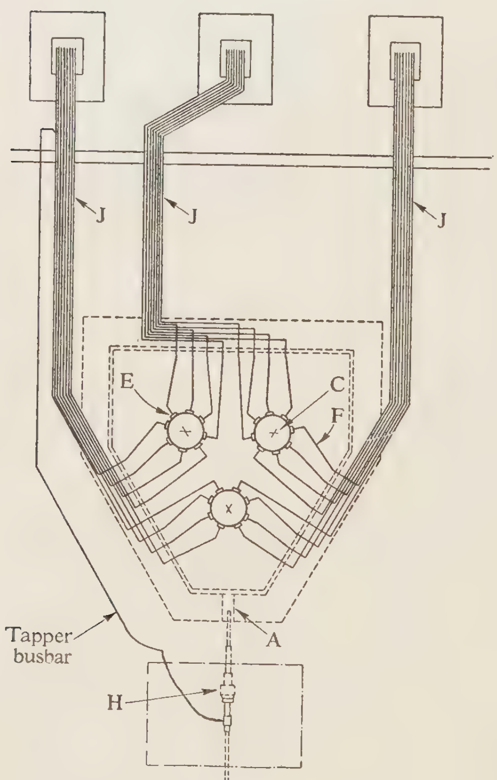

Fig. 5B.—Diagrammatic part plan of furnace shown in Fig. 5A.

A—Taphole.
C—Soderberg electrodes.
E—Contact shoes.
F—Water-cooled conductors.
H—Tapping-gun assembly.
J—Interleaved busbar stack.

face, is a fabricated steel column arranged for water circulation. These serve to prevent distortion of the shell in the region of the taphole and incidentally provide some measure of cooling against the intense heat when the furnace is tapped.

The bowl itself rests on a lattice work of flat-bottomed rails and rolled-steel joists running at right angles to each other, and this, in turn, is supported on a suitable concrete foundation. To retain the bowl in a vertical position and stiffen the sides, it is surrounded by "A" frames, B, on each face which are also supported on concrete foundations.

Three Soderberg self-baking electrodes, C, of 48 in diameter are immersed in the bowl, which contains the mixture of coke and lime. These electrodes extend vertically upwards to a height of about 40 ft above the top of the bowl through an electrode slipping floor and electrode paste floor, on which are situated three twin-drum hoists for electrode raising and lowering. The weight of each electrode in working order is approximately 20 tons.

A Soderberg electrode consists of an inner cylinder of No. 18 S.W.G. mild-steel sheet with short fins projecting inwards. The lower portion of this cylinder is surrounded by an outer steel cylinder, known as the dust-shield casing, leaving an annular space of about 1½ in all round. The top of this casing carries a mild-steel structure for supporting the Wisdom ribbon gear used for slipping the electrodes. On the top of this structure are mounted two double sheaves, around which are run the steel ropes from the electrode winch, D. Since the whole of the electrode assembly is "live," insulated bolts are used to support the sheaves. From the lower end of the dust-shield casing are suspended, by insulated links, eight brass water-cooled contact shoes, E, which are used to conduct the current into the electrode. Surrounding these shoes, at about their centres, is a water-cooled mild-steel ring which carries eight contact bolts. These are used to maintain good electrical contact between the shoes and the electrode. Air is blown down from the top of the dust-shield casing through the annular space from which it exhausts at the bottom. This serves to cool the shoe-suspension assembly and keep dust from accumulating on it. Electrode paste, made as described in Section 4.3, is poured into the top of the inner cylinder.

With the furnace in a working condition, in that portion of the electrode which is immersed in the hot mixture the volatiles from the bond have been driven off and the whole mass has carbonized. The steel electrode casing has also burnt off. The contact shoes are about 9–12 in above the level of the mixture and, in this portion of the electrode the steel casing has not burnt off and the paste is in a semi-baked condition. Above this point the paste is unbaked. That part of the electrode which is in the bath, being carbon, will react with the lime in the mixture and be consumed during furnace operations. The inner portion of the electrode assembly will accordingly require to be lowered, independently of the dust-shield casing, into the furnace to compensate for this consumption. This operation is called "slipping" and is normally carried out about three times per shift at the rate of about 24 in per 24 hours, depending on the load carried by the furnace.

On each electrode two steel strips, each 9½ in wide and 0·078 in thick, are tack-welded to the electrode casing diametrically opposite to each other. These are known as the "Wisdom ribbons" —so called after their inventor, Wisdom. Each is carried over a series of friction drums and thence through two clamps, the first of which is fixed and the second movable in a vertical direction by means of a screw passing through the clamp body. Normally the ribbons are held tightly in both clamps, but when it is necessary to slip the electrode, three or four shoe contact bolts are slackened off, the top clamps loosened and the lower

clamps moved in the required direction simultaneously, until the electrode has been lowered by the desired amount. The ribbons are then made fast at the top clamps and the lower clamps are returned to the starting position where the ribbons are also made fast in the clamps. Fig. 5c shows the arrangement of the electrode slipping gear.

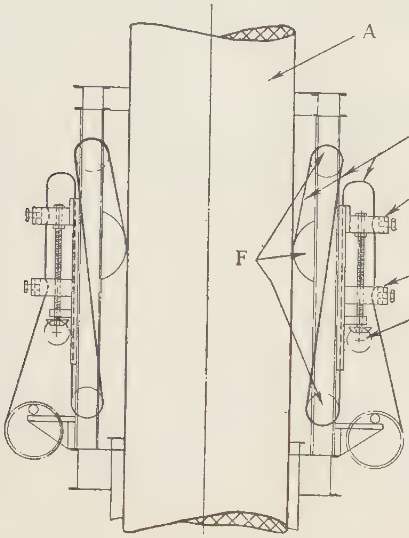

Fig. 5c.—Electrode slipping gear.

A—Electrode.
B—Top clamp.
C—Lower clamp.
D—Operating gear.
E—Wisdom ribbon.
F—Friction drums.

Water-cooled current conductors, F, are arranged between the ight shoes of the electrode and the furnace busbars. As the lectrode assembly is required to be movable in a vertical direcion, a length of flexible conductor is interposed between the two igid sections which consist of copper tube of a suitable section. The flexible section consists of a stranded copper cable laid up round a helix of copper wire to provide a hollow core, the whole eing surrounded by a seamless corrugated phosphor-bronze asing.

The water flow in the shoes is directional and the eight are conected into four pairs by inter-shoe water connections, a comlete water circuit thus consisting of two shoes with their conections. Water flows through the length of a conductor into ne shoe through the inter-shoe connection and into the adjacent hoe and returning through the conductor system into the furnace ffluent tundish.

Other internal parts of the furnace are also water-cooled, otably the ring surrounding the shoes and known as the clamp ng, G. This is of mild-steel fabricated construction in four 90° ections. Each section has internal partitions to give directional ow of the water. The ends of each section are constructed as ne opposite halves of a hinge and are brass-bushed. The four ections are arranged around the electrode to form a complete ng and mild-steel pins are inserted through the hinged ends. he eight equidistant holes through the ring are steel-bushed and readed to receive the mild-steel contact bolts. Copper conections at the ends of each section are used for continuity of the ow and the inlet side of the first section and the outlet of the last e connected to the flow and return pipes, which are led some 0ft up the dust-shield casing. The lowest section of the dustield casing is also water-cooled, the flow and return pipes nning up the casing to the same level as the clamp-ring pipes. o compensate for the rise and fall of the electrode, a length of seamless corrugated phosphor-bronze tubing is inserted between all these pipes and the external pipe system of the furnace. Three such electrode assemblies are required in the furnace, spaced at the apices of an equilateral triangle with sides 102 in long.

Surrounding these electrodes and resting on the top of the bowl is the furnace hood. The lower panels are of non-ferrous metal construction to reduce eddy-current losses and are arranged for water cooling. The upper panels are of mild-steel construction and contain apertures for the entry of the various water services and electrical conductors.

In front of the furnace, on that side of the bowl in which is the taphole, the "tapping gun," H, is situated. This consists of a series of circular graphite electrodes, graduated in diameter from 8 in to 3 in and screwed into each other. The 8 in electrode is clamped in a holder and connected to one of the transformer busbar stacks through a contactor-type isolating switch, situated in the transformer house, and which is controlled from the furnace house adjacent to the taphole. The complete gun assembly, including a wooden handle and flexible cable, is conveniently suspended in front of the taphole and arranged to be retractable from it on a runway beam.

When the furnace is ready for tapping, normally at approximately hourly intervals, an arc is drawn between the end of the gun and the solidified or "frozen" carbide on the outside of the taphole. The passage of current from the gun into the furnace melts the carbide until a new taphole is formed, when molten carbide at about 1 800–2 000° C is discharged into one of a train of cast-iron moulds, usually called bogies, mounted on wheeled chassis. When one bogie is full, the train is moved on and the next is filled. The full train of bogies is allowed to stand for a period of about three hours, after which the "pig" of carbide can be lifted out of the bogie by a crane, and stacked on the cooling floor for a further period of about 30 hours, after which they are ready for passing through the crushing plant. If it is necessary to stop the flow of carbide from the taphole, the gun is withdrawn and shovels of broken carbide, which is usually available on the floor near the taphole, are thrown into the taphole opening, and this is generally sufficient to stop the flow. However, the furnace is normally allowed to run itself completely empty of the carbide which has been formed since the previous tap.

Power is received at the furnace transformer house at 33 kV by underground cable, where it is connected to an open busbar system, via isolators, suspended on suitable insulators from the ceiling. From this system the three single-phase transformers each of 10 120 kVA capacity for 33 kV/220 volt operation are supplied as a delta/delta group.

These transformers are of the shell type and, owing to the low resistance of the furnace circuit between the electrodes, their reactance is kept as low as possible in order to maintain a reasonable power factor on the system. The reactance under normal operating conditions is, in fact, about 1·7%.

The high-voltage windings are tapped to give a secondary voltage range of 220–136 volts in thirteen steps by means of motor-operated off-load tap-changing gear controlled from the furnace control-room. Three current transformers are fitted on the stems of the high-voltage bushings on these transformers, one being for the power-indicating and recording instruments, one for the winding-temperature thermometer heater and one for the automatic furnace-control relays and indicating ammeters. The secondaries of these last current transformers have thirteen taps with a selector switch mechanically linked with the main transformer tap-change gear. This is to compensate for changes in the main transformer ratio, so that its output is a fixed proportion of the electrode current.

The low-voltage windings each consist of eight single-turn coils, distributed between the high-voltage windings. The ends of each coil are taken out individually from the transformer to the busbar stack, which thus contains sixteen bars each of 24 in × $\frac{5}{16}$ in section. The ends of the coils from each of the transformers are connected to the furnace electrode, as shown in Fig. 6, to form the secondary delta circuit. This Figure also shows the complete elementary circuit diagram for a carbide furnace, together with an indication of the reaction adjacent to one electrode of the furnace.

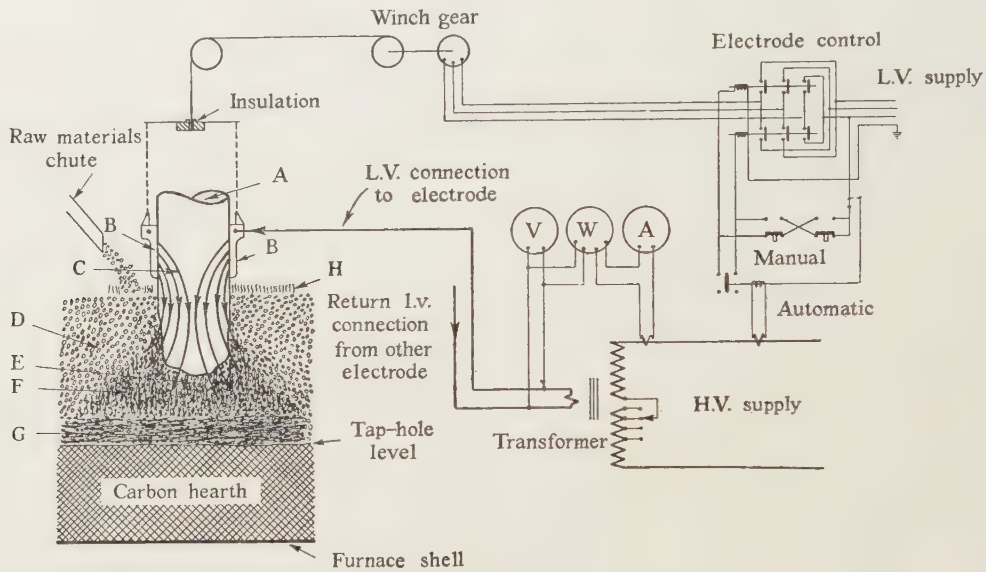

Fig. 6.—Elementary diagram for carbide furnace.

A—Electrode.
B—Contact shoes.
C—Current flow.
D—Lime–coke mixture.
E—Liquid lime–gaseous coke zone.
F—Carbide formation zone.
G—Pool of liquid carbide/lime mixture (80%/20%).
H—Carbon monoxide burning to carbon dioxide.

In the transformer house the busbar stacks are open and supported by suitable insulated clamps. After they have passed into the furnace house and beyond the last connection to the electrode shoes, they are enclosed in a casing. Washed air is blown into the transformer house and is allowed to escape through the busbar casing into the furnace house. This assists in cooling the whole system and, by maintaining a positive pressure, tends to prevent the entry of dust.

In order to obtain 80% carbide, the mixture of correctly graded lime and coke is fed into the bowl in the proportion of 60 parts of lime to 40 parts of coke from the mixture bunkers above the furnace. These proportions are obtained by feeding the lime and coke through automatic weighers into the bunkers. Under working conditions, the mixture can vary and these variations are compensated by "fluxing" from bunkers containing lime and coke separately.

Upon the maintenance of supplies of correctly graded mixture, both as regards size and lime/coke ratio, depends the production of consistent quantities of carbide with a gas yield of $4 \cdot 80\,ft^3/lb$. Any serious departure in the ratio will have its effect on the gas yield of the product. An increase in lime will produce a carbide of lower gas yield, which is more fluid and will thus tap more easily. An excess of coke appears to affect the gas yield far less than lime. Again, oversize of one constituent in the mixture with respect to the other affects the conductivity and will tend to produce a carbide of varying gas yields.

Among other factors affecting the production of good-quality carbide, power cuts must be mentioned. Some idea of the magnitude of a carbide factory load will have been gained by the description of the furnace transformers. Arrangements have been completed with the supply company with whose district control engineer the factory substation attendant is in direct telephonic communication, whereby load is shed by the factory in stages. This is carried out by reducing furnace load, if it is economically feasible, or by switching off a furnace.

If a furnace is switched off for a period, heat is lost and all this must be replaced before carbide can again be produced. The first carbide tapped after a shut-down is always of poor quality.

Change of load on a furnace is obtained by varying the operating voltage. The purpose of electrode movement is to compensate for electrode carbon consumption and to maintain a balance between the three furnace transformers. The electrical characteristics of the furnace are such that, providing the electrode butts are of the right length to give correct immersion and the mixture grading and composition correct, the furnace will operate at its normal power factor on whatever loading is required.

In the course of normal furnace operations, incidents will occur that render it necessary for the furnace to be closed down for repairs. Amongst these may be listed the following items:

Water Leakage.—This can occur in any part of the furnace which is carrying water, such as the contact shoes, flexibles, inter-shoe connections and clamp-ring connections, etc. In the manufacture of these parts, much thought has been given to their design, since the arduous conditions under which they operate are well known, and it was realized that they would have to be renewed in the course of normal furnace operations. Therefore, in the event of any of these parts requiring renewal, the furnace is switched off and the top of the bath smothered with cold mixture, on top of which mild-steel sheets are laid. The maintenance crew, suitably attired in protective clothing, enter the furnace and remove the faulty part, replacing it with a spare. Most of the parts mentioned above can be changed in periods varying from one-half to two hours.

Electrode Faults.—Normally, very little trouble is experienced with the furnace electrodes, but occasionally that part which is

n the bath will become separated from the upper part. In the vent of this happening, a mild-steel plate is drawn through the ap and tack-welded to the casing above it. The broken butt is auled out of the bath with suitable tackle. The upper part is hen "slipped," as described earlier, until it is well immersed in he bath. The furnace is then switched on and a low load naintained for some hours, whilst the "green" paste in the fresh utt bakes. After a suitable period, the load is gradually in-reased to its normal value.

Impurities.—All impurities in the raw materials can cause rouble in the furnace and result in useless consumption of elec-rical energy as they are reduced to their elements in the presence f coke. The most serious of these is silica which is reduced to licon, in which form it will combine with the iron, which is resent from the electrode casings, furnace poking bars and ash, o form ferro-silicon. This is more dense than the carbide and ormally lies just below the pools of carbide underneath each lectrode. As long as the ferro-silicon comes out of the furnace vith the carbide, no serious troubles occur. Sometimes, how-ver, the ferro-silicon will build up and find its way through weak arts into the refractory lining and burn right through the mild-teel shell of the bowl. In the event of this happening, the break-ut is allowed to continue running until the ferro-silicon has all ome away and has been followed by carbide, after which the arbide is allowed to solidify when the furnace is switched off for short period.

4.5) Carbide Crushing, Screening, Packing Plant and Drum-making Plant

The cool pigs of carbide, as such, are unsuitable for the market nd must be crushed and screened into the various grades stipu-ated in the British Standard for carbide (B.S. 642: 1951), amely 50–80mm, 25–50mm, 15–25mm, 7–15mm, 4–7mm, -4mm and 1–2mm.

Some large consumers, owing to the type of acetylene generator sed, prefer a carbide which is a composite mixture of all the bove grades and is usually called "chemical carbide" or 1–80 mm arbide.

The carbide pigs are first passed through the crushing plant, which comprises a breaking table on which the pigs are dropped rom the height of about 4ft. From this the large lumps (up o about 18in cube) are carried on a steel-tray conveyor to a rimary jaw crusher, which reduces the carbide to approximately in cube size. The rate of feed into this machine is controlled y a Ross chain-feeder. From this crusher the carbide is carried y another tray conveyor to a secondary jaw crusher, which educes it to approximately 4in cube size. The material then asses over a screen which rejects the carbide over 80 mm into a rtiary crusher of the gyratory type for reduction to 80 mm, hilst the material below this size passes forward to the main orage bunker to which it is elevated by a skip hoist.

It is extracted from these bunkers to pass forward to the rading plant. The screens are of the multi-deck vibrating type, riven by electric motors. Oversize material is returned to a ving-hammer-type crusher for further reduction. Magnetic parators are used to remove the particles of ferro-silicon which e produced in the furnaces.

The various grades of carbide are then passed to the graded ze bunkers, from which each grade is packed as required into eel drums of either 1 or 2 cwt capacity.

The automatic packing machines consist of a vibratory feeder hich delivers the carbide at a controlled rate into a weigh-box, ounter-balanced at the correct weight on a beam. As the box oves into weighment, the current to the feeder is cut off by a vitch operated by the beam. Another vibratory feeder is started up when the operator is ready for the carbide to be delivered into the drum.

Immediately after leaving the packing machines, the drums pass over check-weighing machines. The drum lids are then put into position and clenched over to render them watertight. After this, the sealed drums of carbide pass by conveyors to the warehouse and loading bays for dispatch.

The complete requirements of drums necessary for the packing of all carbide produced in the factory are manufactured in a drum-making plant, situated adjacent to the carbide screening plant.

(4.6) Electricity Supply

The factory derives its electricity supply from a special sub-station of the B.E.A. with a direct connection on to the main Grid system.

The main factory substation consists of a switch-house and control room. The switch-house is divided into two approxi-mately equal parts, one for the 33kV and the other for the 11kV switchgear. The 11kV side also contains sections for the sub-station low-voltage distribution boards and batteries for switch operation and indication services. The control room contains the metering, protection and remote control-gear for the main switchgear and transformers. Supply to the factory from the B.E.A. is at 33kV and to provide this the B.E.A. substation is equipped with two 45MVA transformers with on-load tap-changing gear.

Referring to Fig. 7, it will be seen that duplicate 33kV feeder cables, each comprising two sets of $3 \times 0{\cdot}5\,in^2$ paper-insulated lead-covered cables in parallel, terminate at oil circuit-breakers of 750MVA rupturing capacity. These are connected to main or auxiliary busbars, as desired. The main busbars are divided by a busbar-section switch, but the auxiliary busbars are solid. From these, supplies are taken through oil circuit-breakers of 500MVA rupturing capacity to the carbide furnaces and the two 33/11kV 10MVA transformers.

The 11kV feeders from these two transformers terminate on oil circuit-breakers of 150MVA rupturing capacity connected to main or auxiliary busbars. As before, the main busbars are divided by a busbar-section switch and the auxiliary busbars are solid. Supplies from this board are taken to the two anthracite calcining furnaces and the two site substations.

Each site substation is equipped with an 11kV switchboard for distribution to the two 2MVA 11kV/400volt transformers and the 11kV tie between the two. There is also a 400volt switchboard carrying air-break switchgear for distribution to the various factory buildings.

In addition, one substation is provided with a 1 000h.p. Diesel engine and 700kW 400volt alternator. This is connected to the 400volt busbars by an air-break switch, but no arrangements are made for synchronization with the public supply. The alternator is regarded purely as an emergency supply to keep the essential services, such as cooling-water pumps and lighting, running in the event of failure of the public supply. The station is continuously manned and the attendants are trained to get the alternator running and switched on to the busbars in under 15min.

All main distribution between substations and buildings is by means of paper-insulated lead-covered cables at the three voltages used. Low-voltage distribution boards are equipped with h.r.c. fuse-gear, with a rupturing capacity of 25MVA. All low-voltage cabling is in copper-sheathed and mineral-insulated cable.

It will be appreciated that the carbide furnaces comprise over 95% of the load and, as such, have by far the major effect on the operating power factor and load factor.

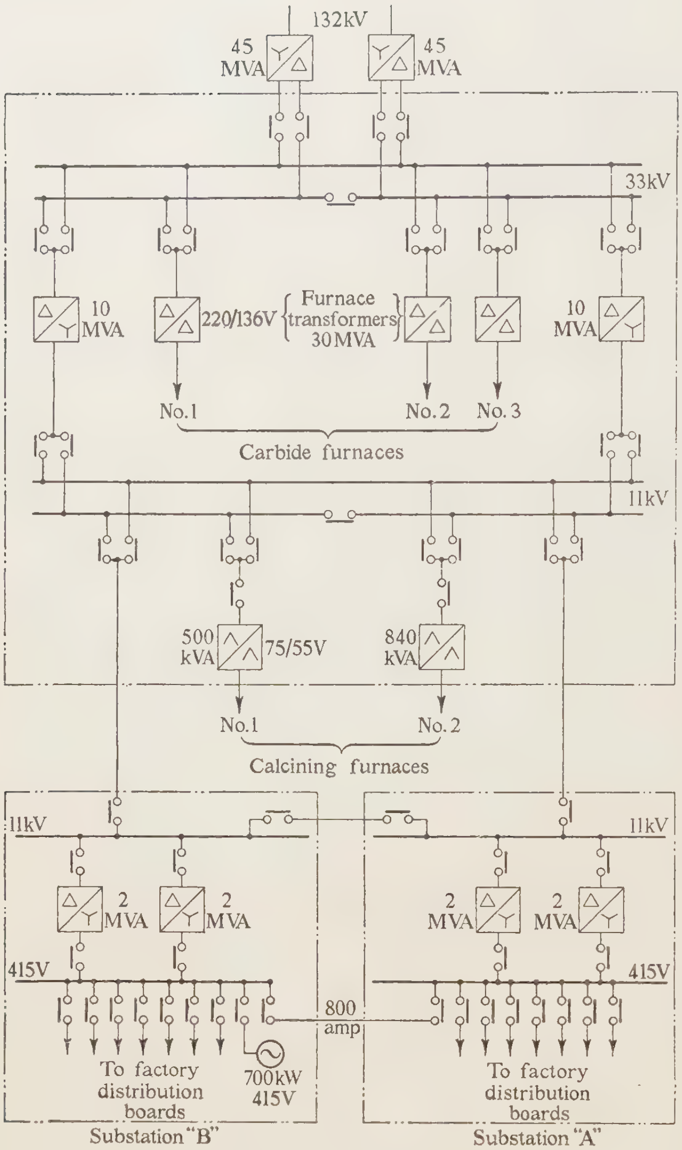

Fig. 7.—Main power circuits.

By careful attention to design, both of the furnace transformers and of the furnace busbar system, it has been possible to maintain a power factor of between 0·85 and 0·88. Little, however, can be done with regard to load factor when, in the event of a furnace stoppage, such a large proportion of the total load is dropped.

With average weekly furnace running times of over 97% under normal conditions, the reliability of this type of furnace seems to be fully proved, and average monthly load factors of over 70% are attained. On the 33 and 11 kV systems, fault protection consists of two overload relays and one earth-leakage relay, whilst on the 400 volt system three overload relays are provided.

All the electric motors used in the plant are of the totally-enclosed fan-cooled type, complying with B.S. 168 : 1936. The choice of squirrel-cage or slip-ring motors is dependent on the starting conditions but, wherever possible, plain squirrel-cage motors are used.

The majority of starters are of the manually operated type, and sequence interlocking is adopted whenever considered necessary for operational reasons.

(4.7) General Services: Water, Compressed Air, Workshops and Transport

A considerable volume of water is required for cooling in the operating parts of the carbide furnaces, calcining furnaces, lime kilns and for other sundry duties, and two pumping stations, together with cooling ponds, are provided for this purpose. Under normal operating conditions in the factory some 250 000 gal/h are circulated through the plant. Evaporation and other losses, amounting to approximately 5%, are made up from two shallow wells on the site.

Compressed air is used on portable tools around the factory and also for operating various mechanisms on some of the production units. There are two air-compressor stations which normally supply two separate mains at a nominal pressure of 70–80 lb/in^2. In the event of emergencies, the two mains can be coupled together.

The repair and maintenance of all production units is carried out by the engineering department. Fabrication of some of the major items of special plant is also carried out in the workshops, of which there are two, one being devoted solely to the maintenance of the drum-manufacturing plant. A selection of the usual workshop machinery such as lathes, milling machines, drills and shapers is provided, together with a blacksmith's shop, coppersmith's shop and an electrical repair section.

For every ton of carbide dispatched from the factory, very nearly 3 tons of raw material are received. Road and rail transport is provided and is serviced by the engineering department. The raw material dump is arranged alongside the main sidings and materials are recovered from it by two electrically operated transporter cranes. Wagon tipplers are installed at suitable positions along the dump. Electric battery trucks are used in the carbide warehouse for the movement of packed and empty drums. Charging facilities are available in the warehouse and the trucks are serviced by the engineering department.

(5) SAFETY

So far as the general run of mechanical plant is concerned, the provisions of the relevant sections of the Factories Act must be satisfied.

In carbide manufacture there are, of course, risks peculiar to the industry and measures must be taken to safeguard against these. One of these concerns carbide itself. In the presence of moisture, acetylene is liberated and this gas forms an explosive mixture with air. In the first place, therefore, the buildings in which carbide is present must be maintained completely weather-proof. Secondly, in the carbide crushing plant, water must not be used for cooling of bearings; instead oil is used, and this is subsequently passed through a water/oil heat exchanger away from the carbide.

It may be thought rather odd that, in spite of the above precautions to keep water away from carbide, water is used to cool the carbide furnace parts. The reason for this is that, owing to the flame present over the furnace bowl, any acetylene produced would burn safely away.

Certain precautions are also necessary on the furnace. It has already been mentioned that the electrode casings are lengthened by welding on sections *in situ*. This is carried out whilst the furnace is on load, and it will be appreciated that the operators are therefore working on metal which is electrically energized. In order to prevent them from touching the other phases, wooden barriers are erected between the three electrode assemblies on the paste floor.

Grease points on the electrode hoist sheaves are carried down in brass tube to be easy of access, and although these sheaves are themselves insulated from the electrode, it has been thought

necessary to provide a further safeguard by the insertion of a length of rubber tubing in each grease line.

During the course of furnace repair work, electric welding may be used on various parts of the electrode assemblies. At the same time, men may be required to work on the furnace transformer tops adjacent to the high-voltage bushings. As there is a possibility of a high voltage appearing on these bushings, it is laid down in the "permit to work," issued before any person can enter the transformer house, that the oil circuit-breakers at the main substation must be opened and the high-voltage busbars in the transformer house must be earthed before work on the transformers is begun.

If a furnace is shut down for work which requires men to go inside the hood, it is again laid down that the furnace must be switched off and the main isolators in the transformer house opened. A "permit to work" is also issued for this purpose, which allows the duty electrician to enter the transformer house and open the isolators. The permit also stipulates that the control of the main oil circuit-breakers at the substation is changed from remote to local.

It will be realized that, in the course of working on repairs inside the furnace, men will perspire very freely. All portable lighting, therefore, is supplied at 50 volts with the centre point earthed. This also applies to other parts of the factory for similar reasons of general safety.

The only other risk peculiar to the industry is that of sparks from electric or gas welding or cutting in an area where there is a likelihood of acetylene being present. To guard against this, an explosimeter is used in the area or space concerned. This instrument registers the percentage of acetylene present in a sample of air drawn through it. It is laid down that the instrument must be used and the results recorded before any welding work is carried out. Should the instrument indicate that the amount of acetylene present has reached a dangerous value, measures must be taken, by the person responsible for the work being carried out, to reduce the amount of acetylene by purging or other suitable means, before commencing to use the welding apparatus.

(6) ACKNOWLEDGMENTS

The author wishes to thank the Distillers Co., Ltd., as Agents for the Ministry of Supply, for permission to publish the paper. He also wishes to acknowledge the help given by his colleagues in checking the draft of the paper.

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DISCUSSION BEFORE THE UTILIZATION SECTION, 18TH NOVEMBER, 1954

Col. W. E. Dennis: I find on looking at the paper that there is no mention of possible faults. With very heavy currents, even at low voltage, I should have thought there would be considerable danger to transformers and busbars. I should be grateful if the author could give me some information on this and on what method is adopted to limit the effects of faults. There is a 132 kV system coming in and there is only the 45 MVA transformer between that and the furnace transformers. Is any effect felt in the transformers if there is a surge on the 132 kV line?

I notice the busbars for the transformers feeding to the electrodes are made of 24 in $\times \frac{5}{16}$ in copper. Why have copper tubes not been used? In Germany they use copper tubes.

With the shoes being subjected to considerable slip, and the heavy currents that flow between the shoe and the electrode, has the author any method that will indicate to him that there has been arcing and, since there is a liability of damage to the shoe, that shoes are damaged?

The author mentions that the energy rate of carbide production is 3 500 kWh per ton. Could he give any figures indicating the proportion which is due to tapping or inform us of any other methods of tapping and whether they have been tried out?

Mr. E. Robertson: The carbide plant described by the author was designed in the early days of the 1939–45 War and was rushed into production in view of the vital need for calcium carbide to further our war effort.

Electrically the plant was designed so that a single bomb falling on any part of it would not unduly interfere with production, although spare 33 kV and 11 kV switchgear was held available in case the main substation received a direct hit.

The main auxiliary transformers of 10 MVA rating are high in view of the author's remarks that only 5% of the power is required for auxiliaries. Actually it was intended to construct an additional plant, but the scheme was abandoned too late to enable a reduction in the size of these transformers to be made.

In the early days a number of very severe short-circuits took place in the busbars, and resulted in a considerable amount of damage. I should be glad if Mr. Beavis would give information on the cause and the extent of the damage, with particular reference to the l.v. busbars and 33 kV transformers and switchgear, in view of the fact that the system has an extremely low reactance.

The power factor, 0·85–0·88, seems to have been decided in an arbitrary manner, although the operating results would appear to have justified the compromise between a system of higher reactance against the increased cost of power charged on a maximum-demand kilovolt-ampere basis.

The addition of power-factor-correcting condensers might well be justified, although their value to the system during the night is questionable since the reactive power will probably contribute towards greater system stability under conditions of normal night loading.

Mr. W. P. Warren: My first point has some bearing on the closing remarks of the previous speaker. I do not think one should lose sight of the fact that the installation referred to in the paper is situated in a predominantly industrial area, where the system load factor is already in excess of 60% and load characteristics are not vastly different between the hours of day and the hours of night.

The author mentions that the whole of the installation has an average power factor of between 0·85 and 0·88. This, at a load of 55 MW, means kilovoltampere-hours (lagging) to the extent of some 32 000. No doubt, the charges for supply are dependent on the power factor. I realize it is possible that there is an inducement to correct.

Taking the power factor with a minimum limit of, say, 0·98, to obtain this figure would require some 20 000 kVAh (leading). I should be grateful if the author would give some indication as to the manner in which such correction could be

effected. The alternative would appear to be rotary synchronous condenser or static capacitor.

Rotary correction as applied to an arc furnace load has much to commend it, but owing to conditions enumerated by the author it would appear to have the following disadvantages.

The majority of the load is utilized at 33kW, which in these days is regarded as somewhat too high for normal rotary application. But with this submersible-electrode type of furnace, as compared with the withdrawable type of electrode normally associated with steelwork production, the switch duty is not as frequent. With such a high load factor and with a continuous load, as in this instance, the more accurate and expensive automatic control facilities available with rotary correction are not justified.

With static correction the capital charge, maintenance and running losses are much less, but again difficulties arise when one considers the switching of capacitors at high voltages.

There is already in South Wales an installation consisting of a 1 500kVAr 33kV capacitor plant, comprising three 500kVAr 19·1kV units. This bank was used for the correction of a 4MVA steel-type arc furnace, and the bank is looped between the 33kV circuit-breaker and the primary of the circuit transformer. It was thought better to put the capacitor in at that point, because 1 350 of the total 1 500 was accounted for by the reactance of the transformer. Even though the electrodes were withdrawn as long as the transformer was energized, the transformer still accounted for 1350 of the total 1500 that was being put into the installation.

In this particular installation in South Wales, there had been some difficulties in contacting work. It now appears that these will be overcome by the fitting of absorption resistance across the interrupter contacts. I believe this is one of the first—if not the first and still the only—33kV capacitor installation in the country already switched at 33kV. There are many bulk installations of both 33kV and 11kV capacitors normally associated with the Grid system, but in the majority of instances those capacitors are switched on the primary side of the transformer at 66 or 132kV for switching with the 33kV condenser.

In view of the difficulty of switching, I wonder whether the author has encountered any difficulty in using 33kV capacitors in the installation, particularly bearing in mind that the 33kV switchgear he has described is oil filled, and the switchgear to which I have referred is air blast, which is normally understood to withstand heavier duty.

A great deal of research still appears to be necessary into capacitance switching and protection. I include in this the wider field of series capacitors for line regulation. I should be particularly glad if the author would comment on the results of any investigations he may have been making into this subject with a view to improving on power factor in the particular installation with which he is concerned.

One other point on load factor. In carbide production the cost of electricity is probably the largest component in production costs. Hence, operation at as high a load factor as is possible is desirable. In the paper there was mentioned a monthly load factor of some 70%, which means the annual load factor would probably be some degrees lower. Is this figure the highest which it is reasonably possible to obtain? I put this question, bearing in mind the possibility of having permanently available a standby furnace in the event of any breakdown or prearranged maintenance of the normal production furnace. This would, indeed, have the effect of increasing the load factor considerably and so reducing the cost of electricity per ton of carbide.

Perhaps the author would give his opinion on the merits of justifying this additional capital outlay as against a saving in the overall production costs.

Mr. A. J. Dawson: I was intrigued by the author's comment that the production of carbide does not require an electric arc.

This statement does not lead to the conclusion that the furnace is really a resistance furnace (a query raised by a previous speaker and perhaps inspired by the high power-factor of the furnace) and I should like to associate myself with the author's picture of an arc zone and a resistance zone. But the relative magnitude of each is important, and I should like the authors' opinion as to what percentage of total furnace energy he thinks might appear in his arc zone. In somewhat similar furnaces of the "submerged arc" type operating on phosphorus manufacture I have observed third-harmonic values of about 8% and fifth-harmonic values of ½% in the secondary current. It seems very probable that the carbide furnace shows figures with a lower percentage.

The author has stated that any phosphorus present in the mix appears in the carbide. I presume it mostly appears as calcium phosphide, which naturally would be unwelcome. It seems possible to me that some of the phosphorus might go forward with the iron to form ferro-phosphorus, and I would like to know what proportion, if any, finds its way into the ferro-silicon.

In speaking of the furnace, the author has been very modest about the difficulties of taking out electrode stumps from a furnace that is virtually white hot. I am quite sure that this is a very ticklish, difficult and unpleasant problem. Perhaps he might tell us how frequent are such happenings—how often the ferro-silicon breaks through the side of his furnace, and how many months or years he would expect to operate his furnace without shutting it down. This is important, too, from the point of view of switch operation. One naturally wonders how often he has to change the oil in his circuit-breakers, how often the furnace switch is operated each month and whether it is customary to reduce the load before operation.

It is clear that the cost of electricity represents a fair percentage of production costs. Can the author give us some idea of this figure?

In view of the fact that this plant was put down in the early days of the 1939–45 War, one wonders whether the time has now come, if the job were to be repeated, to put down closed carbide furnaces. One would like to know whether the economies that might result from the heat saving and the gas collection which could be used for drying the raw materials would justify the serious additional difficulties the author would encounter in handling his broken electrodes.

Mr. E. W. Rodnight: I should like to emphasize the questions put to the author by Messrs. Warren and Dawson relating to power factor and power consumption. The combined effect of power consumption and power cost forms an extremely large part of the overall cost of producing carbide.

I should like to know whether, if the author were considering the design of a new furnace from the electrical point of view, he would be able to achieve a much higher power factor than at present. Would he, for instance, consider a radically different design of furnace, such as a single-phase furnace of the Miguet type? Many are operating at very low energy consumptions and high power-factors, although there are a number of other aspects which make them less desirable for large-scale production.

Mr. Leslie Smith: I am particularly interested in that I have in some degree been concerned with the furnace transformers. Earlier speakers have mentioned one or two of the hazards, and a comment or two from me might be of interest.

It has been said that short-circuits occurred on the busbars in the early days of this equipment. My recollection is that they were initiated by surges occurring on the primary side of the furnace transformers, probably due to 33kV switching. Owing to the very low reactance of the transformers, the great amount of interleaving between h.v. and l.v. windings had allowed

transference of these switching surges to the 220-volt busbars in a greater proportion than one would normally find in a transformer of more normal reactance.

At a later period, I recollect that various steps were taken on the l.v. side of the furnace transformers to limit the surge voltages that appeared on the 220-volt busbars to a figure below that at which they could flash over.

In installations of this kind this is a very special feature that has to be watched. In other words, switching surges on the 33 kV side that can be regarded as quite normal, do, in such a low-reactance transformer, transfer themselves to the l.v. busbars and appear as quite high surge voltages in relation to the l.v. circuit voltage of 220 volts.

The author says that he totalled up the resistance of the furnace and various other design features, and he indicates that there was a value left which the transformer designer can achieve in his design. He would have been nearer the truth if he had said ". . . can *just* achieve in his design." For a 30 000 kVA 220 V furnace transformer bank, 1·7% is getting near the lower limit.

As to short-circuits that occur on the l.v. busbar installation, again my recollection is that so far as the furnace transformers were concerned there was no movement of any kind. On the first bank it was noticed, however, that there was a small amount of movement of the busbar connections on the low-voltage side of the transformer. Steps were taken to give additional bracing to these connections, and so far as I know, neither on that transformer bank nor on the others in the installation have there ever been any movements since. I have heard, however, that there are still busbar short-circuits very occasionally; these occasions are infrequent since steps were taken to limit surge voltages on the lower-voltage side and are now only due to dust.

Mr. J. Vaughan Harries: Is it observed that the substation is situated on sand hills and is very near to the sea? Has the author any experience of hazards as the result of salt spray or dust from the sand hills as to call for special consideration either in the design of the equipment or its maintenance?

[The author's reply to the above discussion will be found overleaf.]

SOUTH MIDLAND SUPPLY AND UTILIZATION GROUP, 8TH NOVEMBER, 1954

Mr. E. May: The process which the author has dealt with is one of several electro-thermal processes, all of which require high temperatures, a lot of heat energy, and all of which are carried out in submerged-arc electric smelting furnaces. They are all processes in which an oxide is reduced by an endothermic reaction with carbon. Calcium carbide is probably the most important of the products of all these processes, but others which are also quite essential, e.g. ferro-alloys, including ferro-silicon and ferro-chrome, are vital to our steel industry. In 1943 Mr. A. G. Robiette* pointed out the folly of not having a sound electro-chemical and electro-metallurgical industry in Great Britain; we were buying almost all our products of that kind from abroad, chiefly from Scandinavia. It seems that since then we have developed a calcium carbide industry which is sufficient, or nearly sufficient, for Great Britain. The sterling value of imports of calcium carbide last year was only a little over one-third of that in 1938. On the other hand the value of our imports last year of ferro-alloys, particularly ferro-silicon and ferro-chrome, were nearly nine times as much as in 1938. We have apparently done nothing about the ferro-alloys. Mr. Robiette put forward a scheme to make use of off-peak power from the hydro-electric power scheme in Scotland. The fact is we just cannot compete on economic grounds with ferro-alloys which can be bought from abroad, especially when using electrical energy from thermal stations. In Scandinavia these materials can be made economically by utilizing water power.

I should like to ask the author, first of all, is Great Britain largely self-supporting for calcium carbide now, and is it an economic process as distinct from a strategically vital process? Secondly, would he care to venture an opinion as to the ferro-alloys being a sound proposition for manufacture in Great Britain, particularly with regard to the hydro-electric power of Scotland?

The transformers for the furnaces described have off-load tap-changing gear, and it may be of interest to note that a recently commissioned direct-arc furnace for steel making has a 15 MVA transformer with on-load tap-changing gear, for a range of 90–325 volts. The author's scheme of electrode control shows control on current only, whereas many direct-arc furnaces now operate with amplidyne control responsive to both voltage and current of the arcs. I should like the author's opinion as to whether there is any advantage in using this form of control on large smelting furnaces?

Mr. A. J. Dawson: On the question of furnace design I think it true that, in general, the highest powered furnace has the lowest energy consumption per ton of product, provided that its design is sound. In striving for this energy efficiency we must consider the possible costs that can arise from the failure of a large single unit. There is a very large power account that can arise from the failure to maintain an already established maximum demand. There is the complication arising from re-organization of process labour, the pressure on maintenance staff to complete the furnace overhaul hurriedly, and the complications that can arise from re-direction and control of raw materials. With these and other considerations in mind, does the author feel that there is a maximum, or perhaps, optimum, size of furnace that is best suited to conditions in the United Kingdom? Such knowledge is valuable to transformer and switchgear manufacturers in giving them guidance as to possible future trends.

Still referring to the carbide furnace itself, I am not clear whether the carbon hearth is in contact with the steel shell or whether a refractory lining exists between the hearth and shell. I would also like to know what arrangements are made for earthing the shell and carbon hearth.

The author refers to an electrical tapping gun but makes no comment as to whether an oxygen lance can be used as an alternative—neither does he say whether there would be any advantage in so doing. I gather from the ease with which electrical tapping can be employed that calcium carbide is quite conductive at low temperatures. Can the author give us some knowledge of this figure and its variation with temperature?

Referring to the formation of ferro-silicon, it would be of interest to learn the chemical analysis of this by-product alloy, and to hear at what percentage of silicon it becomes non-magnetic, particularly in view of the author's comment that the ferro-silicon is separated out magnetically. One wonders whether the introduction of iron via the Soderberg electrode casings has lowered the grade of this by-product or has, in fact, assisted operation by fluxing away unwanted silicon.

On the subject of Soderberg electrodes, in a paper by Sem* emphasis is put upon the need for frequent and regular times of slipping of the electrodes in order to produce high-quality baking. Details are given in the paper of new types of electrode

* Paper read at a joint symposium of the Institute of Metals and North of Scotland Hydro-electric Board, 1943.

* SEM, M. O.: *Journal of the Electrochemical Society*, 1954.

clips which are claimed to have superseded the Wisdom ribbon type.

Mr. P. M. Martin: Can the author give some more information regarding the current clamps on the electrodes? Compared with steel-furnace practice, the impression one gets is that the clamp rings and shoes appear somewhat flimsy to pass the enormous currents involved.

I presume that the electrode casing is made from mild-steel plate which may have some mill scale on the surface. Does this surface have to be cleaned or otherwise prepared before the shoes are clamped up, and do the shoes have a ground finish on the contact face? Perhaps the author would tell us whether much trouble is experienced with arcing and burning at the shoes.

Mr. W. A. Vivian: I should be interested to know the present-day method of getting the paste packed into the 4ft-diameter steel shells of the electrodes.

In the early days I think a man used to be lowered into the live shell in a bosun's chair and the paste was tamped to consolidate it around the radially located fins, etc., inside the shell.

A lot of problems arose concerning such 3-phase arc furnaces having a voltage range up to about 220 volts between electrodes, and various safeguards were provided, including those to prevent a person contacting two electrodes at once.

Attempts were made to provide earth-free zones on certain floors around such furnaces, and not only in the case of those used for the production of calcium carbide. Where the distance between the upper parts of the electrodes was too small for easy access when required, with fixed insulating barriers, heavy asbestos curtains have been hung between electrodes to prevent a person from bridging them.

The author referred to not requiring flameproof gear. In this respect it might be mentioned that no Buxton certified flameproof gear is available for acetylene or for certain other gases, including hydrogen and carbon bisulphide.

I recall one explosion of acetylene gas in a high building in which there was a considerable quantity of calcium carbide. A large water pipe in this building became broken, and in consequence acetylene gas was generated and formed a highly explosive mixture with the air. It was ignited and the resulting explosion caused extensive damage to the building.

Dr. H. G. Taylor: A large amount of carbide is absorbed in the welding industry, but I should like to know what percentage this is of the total output and where the remainder is used.

Could the author tell us how one starts up initially with the Soderberg electrode, and also whether there is a very considerable change of resistance when you start up the furnace from cold.

Also I should like to refer to the alloy clamps, which I gather are 85/15 brass; I should have thought that a good case could be made for chromium-copper which has a much higher conductivity.

Finally, does the author have any trouble with circulating currents in these large and extensive busbars between the transformers and the furnace?

Mr. D. B. Corbyn: I am interested in the safety precautions taken in this plant. From the author's description it appears that the transformers have sandwich windings with alternate primary and secondary coils. Reference is made to the dangers caused to men working on the plant by the 220-volt supply to the electrodes.

Are any special precautions taken to guard against insulation breakdown between primary and secondary windings in the transformer itself? Special measures are often required in low-voltage electrochemical plants feeding electrolytic cells, and I wondered whether similar precautions had to be taken in this type of plant.

The second point is this. The quoted power factor is very puzzling. The furnace is described as a submerged-arc type, and I wonder whether it takes a sinusoidal current from the supply or if the phase current is, in fact, greatly distorted.

A power factor of 0·85–0·88 is given, which corresponds to a total percentage reactance of the order of 50%. It is specifically stated that the transformer leakage reactance is only about 2%, and even if one allows 10% for the supply reactance, which is reasonable, there is still a very large discrepancy.

It appears that the input current must be greatly distorted and that the power factor given actually includes a very large distortion factor such as one considers when discussing the input power to a rectifier.

The point is of considerable importance. If the low power factor is, in fact, caused by distortion, it cannot be corrected by means of condensers. It appears possible to make a very great improvement by feeding each of the three furnaces through a suitable phase-shifting transformer in a manner similar to that used with large rectifiers to improve the waveform of the supply current.

The third point concerns the material of the furnace hood. It is stated that the lower panels are of non-ferrous metal to reduce eddy-current losses. It is presumed that this particularly applies to panels near the busbars. In some cases, I know from experiment that eddy-current losses in a leakage field may be less with ferrous sheets than with non-ferrous sheets such as copper. This apparently paradoxical effect is due to the much higher resistivity of steel with respect to copper. It is difficult to generalize, but the effect occurs where the configuration is such that the leakage flux path includes a long air path, and the addition of the ferrous sheet does not greatly alter the leakage flux density.

It would be most interesting to have the author's experience on the construction of the shield on his furnace.

THE AUTHOR'S REPLY TO THE ABOVE DISCUSSIONS

Mr. C. J. Beavis (*in reply*): In reply to Col. Dennis and Mr. Robertson, faults do occur occasionally on the low-voltage furnace busbar system. When one occurs there is generally some loss of copper from the busbars and the clamp insulation usually has to be renewed, but the damage appears to be restricted to the parts in the area of the fault. The transformers do not appear to suffer any ill effects. Some years ago, the Electrical Research Association was asked to investigate these faults and, on their advice, a bank of 3μF condensers was connected across the busbars to earth. This tends to limit the effect of external voltage surges.

I think the real answer as to why tubular busbars were not used is that flat busbars were probably the material most easily obtainable at the time the factory was built—at the beginning of the 1939–45 War.

There is no accurate method of determining whether there has been arcing between the shoes and electrodes, although work is being carried out in an endeavour to throw some light on this matter.

The energy rate for tapping is generally between 20 and 30kWh/ton. I believe that an oxygen lance has been tried, but I understand that this method proved more expensive than electric tapping.

Mr. Warren has raised the question of power-factor correction, and I can inform him that a project is now in the course of preparation for the installation of correction equipment. It is

intended to use static condensers for this duty. Rotary synchronous condensers were considered but turned down—largely on account of cost. It is intended to install the condensers on the 11 kV busbars, since it was considered that the switching duty at 33 kV would be too arduous for the existing circuit-breakers.

Investigations have been carried out to detect the presence of harmonics during various furnace operations, and although the full report of these investigations is not yet complete, it is evident that there were no serious harmonics present, even during the periods when the furnaces were being started up from cold, before the electrodes were closed in with the charge material.

Mr. Warren also mentions the load factor of the factory. He is quite correct in assuming that the cost of electricity is the largest item in carbide production. It is, in fact, somewhat over 50% of the total cost. Load factors considerably higher than 70% are obtained for certain periods of furnace operation, but the figure of 70% was given as an average.

I am glad to have Mr. Dawson's agreement with my idea of an arc zone and a resistance zone in the furnace. No figures are available on the division of energy between the arc zone and the resistance zone, and I am afraid I am unable to give him any information in reply to his question.

Of the phosphorus present in the raw materials, approximately one-half appears as calcium phosphide in the carbide, and almost all the rest is lost in the stack gases. The quantity appearing with the ferro-silicon is insignificant.

In reply to Mr. Dawson's question regarding broken butts, it is difficult to give definite figures for these. Generally, many months elapse between the occurrences, and no definite reason can be given for them as yet, although many differing theories have been put forward from time to time, but these have not, so far, been verified. The repair is carried out by plating across the bottom of the electrode casing at some convenient point above the break, and then hauling the broken butt from the furnace bath. The repaired electrode is then lowered into the bath and closed in with mixture, and the electrode allowed to bake under low load until such time as it is ready for production.

I have already mentioned the relationship of the cost of electric power to the total cost of carbide and, in reply to his query regarding "closed" furnaces, I would say that if further furnaces were to be constructed, there is no doubt that units of the closed type would be used. In closed carbide furnaces, the carbon monoxide can be used either as a fuel in other sections of the plant, e.g. for lime burning or coke drying, or as a basis for chemical synthesis of some other product. It has been found that the heat content of carbide furnace gas corresponds to about one-third of the electrical power required for the production of one ton of carbide.

Mr. Rodnight again mentions power consumption, and I would refer him to my other replies on this. He asks also whether a radically different design of furnace, such as a single-phase Miguet type, could be used. I do not believe that this type of furnace would be seriously considered these days for large-scale production, owing to the difficulties associated with the power supply to large single-phase units.

Mr. Smith also raised the question of faults on the low-voltage furnace busbars, and his remarks are particularly valuable in that he was concerned with the design of the furnace transformers. I concur with all he says and would refer him to the steps that were taken to limit the surge voltages appearing on the low-voltage busbars.

Mr. Vaughan Harries comments on the closeness of the sub-station to the sand-hills and sea, and also asks for our experience of hazards as a result of salt spray and sand. I think the only occasion when we have been seriously in trouble from these two causes was during the autumn of 1953, when the atmospheric conditions were very abnormal. The wind was blowing from over the sea and the thick mist appeared to be heavily laden with salt spray, and this caused such heavy corona discharges across the 132 kV insulators that, for a time, the factory was completely shut down.

In reply to Mr. May, I would say that Great Britain is now practically self-supporting for its requirements of calcium carbide. At the present world prices, it is an economic process as distinct from a strategically vital process. With regard to the manufacture of ferro-alloys in this country, it must be borne in mind that the consumption of electric power for these products is between 10 000 and 15 000 kWh per ton, and I do not therefore think that their manufacture would be an economic proposition in this country.

Mr. May then asks my opinion regarding the use of amplidyne control on the furnaces. I rather hesitate to venture an opinion on this but, so far as I know, there are many carbide furnaces throughout the world which are equipped with automatic control on current only.

In the first part of his question, Mr. Dawson deals with the size of carbide furnaces, and I agree with his opinion that, in general, the highest-powered furnace has the lowest power consumption per ton of product. The ideal arrangement is probably a multi-furnace factory in which there are one or more large units to take care of what might be called the steady output and a number of smaller units which would take care of the peaks in demand which are bound to occur from time to time.

With regard to the lining of the furnace, there is a refractory lining between the carbon hearth and the shell. The carbon hearth is not earthed and the shell is connected to earth only inasmuch as it is connected to the general structure of the building, the foundations of which, of course, might be regarded as a high-resistance earth.

Experiments have been carried out on the use of an oxygen lance as an alternative to the electrical tapping gun, but I believe that this has been proved to be uneconomic. Calcium carbide is conductive at low temperatures, but I regret that I have no figures available of the relationship of its conductivity with temperature.

The percentage of silicon in the ferro-silicon alloy usually produced varies between 18 and 20%, and this alloy becomes non-magnetic at about 25% silicon.

Mr. Martin is under the impression that the shoes are somewhat small when considering the current in the various circuits. Since all these current-carrying circuits are water-cooled, it is possible to increase the current density in these parts.

The electrode casings are made from mild-steel sheet, and this is not cleaned up or prepared in any way before passing into the furnace. The shoes themselves are ground on the contact face, and very little trouble is experienced provided that they are kept clamped-up tightly at all times.

In reply to Mr. Vivian, the electrode paste is now transferred into the electrode casings by tipping from the trays, which are carried over to the electrodes on the telpher. In the early days, a bosun's chair was used—not for the purpose of tamping the paste in the electrode, but to carry out the operation of joining a section of casing on to the electrode. The method of carrying out this operation has now been changed, so that it is now no longer necessary for the man to be lowered into the casing.

Dr. Taylor first asks for the distribution of carbide in this country. Approximately 50% is absorbed in the welding and engineering industry and 50% into the chemical industry as a raw material.

The initial start-up with a Soderberg electrode is carried out by direct baking of the electrode by means of fires, which are lit

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around the bottoms of the three electrodes. I regret that I have no figures of the change in resistance from a cold start-up to the normal working conditions.

The possibility of using a chromium-copper alloy for the manufacture of contact shoes has not previously been examined. I am grateful, however, to Dr. Taylor for this suggestion, which will receive serious consideration.

So far as I am aware, no troubles have been experienced with circulating currents in the furnace busbar system.

In reply to Mr. Corbyn, I am not aware of any special precautions which were taken by the transformer manufacturers to guard against insulation breakdown between the primary and secondary windings in the transformer itself.

A short time ago, oscillograph tests were carried out at the factory by a firm of capacitor manufacturers in connection with the proposed scheme of power-factor correction. From these tests, it did not appear that the current wave was greatly distorted, and the manufacturers have since informed us that they do not anticipate any difficulties at all in supplying capacitors to correct the power factor.

It will be of interest to Mr. Corbyn to know that the power factor of a very similar furnace installation oversea has been successfully corrected by means of capacitors.

Mr. Corbyn's remarks regarding the construction of the furnace hood are very interesting. I would add that in our experience there have been definite advantages in constructing this part of the hood of non-ferrous metal. One of the other furnaces has an all-ferrous hood, and our experience has shown that the appearance of eddy currents in this furnace is greater than in the one which is constructed partly of non-ferrous metal.

DISCUSSION ON "VOLTAGE TRANSFORMERS AND CURRENT TRANSFORMERS ASSOCIATED WITH SWITCHGEAR"*

SOUTH-EAST SCOTLAND SUB-CENTRE AT EDINBURGH, 15TH DECEMBER, 1953, AND THE NORTH MIDLAND CENTRE AT LEEDS, 5TH JANUARY, 1954

Mr. J. Mendelson (*at Edinburgh*): In the present state of development of synthetic-resin moulding it can be used over wide ambient temperatures, i.e. between arctic and tropical conditions. The material remains firm and must therefore impose mechanical strains on the core iron. Stalloy will therefore probably have to be used. It is not clear whether Figs. 1 and 2 are representative up to 200 VA.

Designs of combined voltage and current transformers appear to have been produced oversea, using normal electromagnetic constructions (11–44 kV) with unearthed primary winding. A saving of one h.v. bushing occurs, and I would be interested in the authors' comments on these designs.

The authors are primarily interested in the complex transient conditions affecting current transformers, and therefore metering receives only passing mention. The purchaser usually has to be persuaded to choose class-BM current transformers, and I wonder whether the term "adequate" in Section 3.1 refers to output only.

Secondary currents of 1 amp will become more common, but certain exceptions will prevent complete uniformity. For example, compounding current transformers used for load compensation of automatic voltage regulators will require the normal 5 amp secondary rating because of the physical dimensions of secondary-circuit components.

In telephone engineering many thousands of standardized safety gaps must be in use. It is strange, therefore, that their application to instrumentation circuits is so reluctantly accepted.

Mr. A. J. Coveney (*at Leeds*): The authors' reference to the penetrating properties of the new synthetic resins prompts me to question what proof or guarantee there can be in this respect. Are these resins dependent on an exothermic reaction utilizing a hardening catalyst with the phenolic resin, and if so, are the authors satisfied that complete polymerization has taken place? With this type of solid insulation it would seem the only test is to dissect a sample from each batch of manufacture, as otherwise there is a risk that, after many years of service, decomposition will occur if the curing has not been complete.

What internal temperatures are permissible before there is any risk of insulation deterioration? Also, in the event of an open-circuit on the secondary windings persisting for some appreciable time, is there any risk of fire?

With regard to the positioning of voltage transformers, and in particular, when resistance-type fuses are not installed to protect the high-voltage winding, we have learned from experience that, on feeder circuits, if the connection is taken from the incoming conductor at a right-angle-bend point, it will be subjected to high-voltage impulses under lightning conditions. On certain constructions of switchgear in the past, lightning surges from overhead lines have been reflected at these points to the extent of arcing over a distance of 5½ in under oil.

The authors' work in deriving formulae and producing curves to indicate satisfactory sizes of current transformers that do not saturate should in my opinion be embodied in the new edition of B.S. 2046 or in a later edition which will apply to transformers for use with balanced-system protection, in order that some standardization can be adopted in future.

Mr. G. Auton (*at Leeds*): In applying solid insulants to current transformers, certain important considerations arise which will not always be immediately obvious from even a protracted series of tests. The differing coefficients of expansion of the insulant and conductors have in previous experiments proved troublesome in excluding moisture. In addition, the permitted temperature for the copper conductor whilst working under fault conditions is approaching the softening point for the insulant, and the mechanical and electrical stress cannot, surely, be maintained for any appreciable period of time.

Reference is made to the use of grain-oriented silicon steels as possible core materials for voltage transformers, and to the difficulty of applying these materials to a suitable core construction. I cannot quite understand from the paper how this problem has been tackled, but I should be interested to learn whether the authors have had experience of type-C cores for this purpose.

Now that we have had an opportunity to study the implications of B.S. 2046: 1953 covering protective current transformers, I feel that, unless correctly applied, it will result in a period of "organized chaos" for current-transformer designers. Many years of habit have contributed to the popular conception that

* GRAY, W., and WRIGHT, A.: Paper No. 1398 M, October, 1952 (see 100, Part II, p. 223).

15VA is the rated capacity to quote when in doubt. More unfortunate is the popular request for class-C transformers for protective purposes.

The application of cold-rolled steels to current transformers is now quite well established, but do the authors feel that the material has satisfactorily overcome its initial difficulties, as design data have varied considerably with the final annealing process?

Reference is made in the paper to the manipulation of burdens in volt-amperes, but I find a greater security in the use of impedances—a practice which is, of course, used in certain other current-transformer specifications outside this country. What is the authors' opinion on a design procedure taking a saturation factor of 20 as standard and expressing the burden in ohms? This certainly facilitates an easier understanding by the ultimate purchaser, and gives the manufacturers a clearer picture of what the purchaser requires.

Mr. R. N. Buttrey (*at Leeds*): I am interested in the authors' claim to have made indoor-type current transformers suitable for impulse test voltages up to 100kV. Does this claim refer to 11kV current transformers? Have such current transformers been constructed in accordance with typical restricted British switchgear dimensions, or more in line with Continental practice where much larger spacing and dimensions are permissible? What impulse-withstand voltage would be expected from a cast-resin design of current transformer complying with the typical spacing and dimensions employed in this country?

The authors mention current-transformer open-circuit voltages of 7–8kV. Would such a maximum figure hold for current transformers having a ratio of, say, 400/5 and a short-circuit rating of 250MVA 6·6kV?

Messrs. W. Gray and **A. Wright** (*in reply*): In reply to Mr. Mendelson we would state that care must be taken in the design of resin-insulated transformers to prevent undue stress on the core. If this is done, any core material may be used.

Voltage transformers having an output of 200VA with class-B accuracy have been produced.

Switchgear in Britain over the range 11–44kV is generally of the metalclad type, and in the majority of cases only current transformers are required. Thus it is not economic to design the switchgear to take combined transformers of the type described.

We cannot agree that the physical dimensions of secondary equipment are increased appreciably by the use of 1amp secondary ratings, since the wire sizes are reduced proportionately.

Spark-gaps in current-transformer circuits may have to handle very large currents when they flash over, and must have a flashover value which will not affect the operation of balanced forms of protection. The conditions are thus more difficult than with telephone equipment, and we feel that such gaps are therefore undesirable.

We would assure Mr. Coveney that the curing of synthetic resins is always complete, as the curing time used is well in excess of the minimum required. Short time ratings of 300°C are possible before deterioration occurs. The material used is thermosetting and does not liquefy when heated. The spread of fire from this cause is therefore not possible. The resins used do burn, but not very readily.

We have not had experience of using the type-C cores referred to by Mr. Auton for voltage transformers, but we feel that they allow the simplest construction when cold-rolled silicon steels are used. These steels cause difficulties when used for current transformers in balanced protective systems, as their characteristics may vary considerably even in one batch of material. A further disadvantage is their high remanence. With regard to Mr. Auton's query on manipulation of burdens, we feel that while B.S. 81 allows several standard secondary ratings, less confusion is caused by expressing the burden in volt-amperes rather than impedance. We agree with his comments on B.S. 2046.

In reply to Mr. Buttrey we would state that 11kV current transformers have been made which will withstand impulse voltages up to 100kV. Such transformers are no larger than those used at present in British switchgear.

DISCUSSION ON "POST-GRADUATE ACTIVITIES IN ELECTRICAL ENGINEERING"*

Before the NORTH MIDLAND CENTRE *at* LEEDS, *9th December*, 1952, *the* SOUTH MIDLAND CENTRE *at* BIRMINGHAM, *5th January*, *the* SOUTHERN CENTRE *at* SOUTHAMPTON, *21st January*, *and the* NORTH-EASTERN CENTRE, *at* NEWCASTLE UPON TYNE, *23rd March*, 1953.

Prof. G. W. Carter (*at Leeds*): The authors are quite clear that they regard research in universities by newly graduated men as not so good a training, nor so effective a mode of obtaining scientific results, as the same research done in industry. I have had the opportunity to discuss this problem with the directors of certain research institutions, and, on the whole, I did not find that they took quite so sweeping a view as the authors; the general opinion was that, for a few really research-minded men, research work in universities is beneficial. The practice of my department is based on this view, so that we accept a few research students, but take care before doing so that they are really suitable.

It is worth pointing out that when a graduate elects to remain at the university for a further year or two, he does so at some financial sacrifice, since the level of research grants is over £100 a year lower than the level of remuneration for graduate apprentices. The research students make a valuable contribution to the life of a university department, forming as they do a link between the teaching staff and the undergraduates. When members of the teaching staff are themselves engaged in research, it is very useful for them to have one or two research students working on allied problems; in suggesting that senior members should continue personal research, the authors are perhaps forgetting that it is difficult for them to do so in isolation and without the complementary research of younger men. It is true that the research of a young graduate benefits the man more than the industry, but that does not discredit it.

I believe that a strong case can be made out for saying that a young graduate may benefit greatly from a period of research in the university. It gives him something that he has not had during his undergraduate course—time to think and consolidate his knowledge. In industry people fulfil specialist functions, and the man who carries out tests is frequently not the same as the man who plans them; in the university the young man has the better training of doing both the thinking and the experimenting himself. Furthermore, the specialists in industry are extremely expert in some fairly narrow field, whereas university teachers are not usually experts, but are able to tackle a wide variety of problems from first principles; I believe that it may be more stimulating for a young man to discuss his work with a

* GIBBS, W. J., EDMUNDSON, D., DIMMICK, R. G. A., and LUCAS, G. S. C.: Paper No. 1265, February, 1952 (see 99, Part I, p. 161).

senior who is not too expert, especially as in some problems progress depends upon finding that the ideas of the expert were partly wrong. For these reasons, I consider that research work in universities may be a training of great value. Of course, it would be better if we could get our research students when they have had a period of industrial experience. If, besides putting into effect the research scheme described in the paper, the authors can also use their influence to enable a few men to spend a further period in the university at the end of their apprenticeship, such men might benefit greatly.

Dr. E. C. Walton (*at Leeds*): The authors are opposed to the creation of new technological universities for the purposes enumerated in the first paragraph of the paper. With this opinion I agree, but I am unable to accept the implication in the last few lines of the paragraph to which I have referred: I cannot believe that the authors would deplore any movement by existing universities and colleges to provide "many more graduate engineers" and to afford "extensive facilities for research and development in all branches of industry."

In my view there is a case for the improved training of selected men from the group pursuing the normal industry-based route, i.e. a five-year apprenticeship coupled with part-time courses leading to Ordinary and Higher National Certificates. This improved training should take the form of industry-based sandwich courses of the type referred to by a previous speaker. The general plan for such a course might be: one year in industry with concurrent part-time attendance at a technical college followed by selection on merit for a subsequent four-year sandwich course (6 months in college, 6 months in industry per annum) and finally a further year in industry coupled with post-graduate training. This type of course offers a wider and deeper training than is possible with existing National Certificate schemes. The existence of such courses should encourage boys from secondary grammar schools who might otherwise be attracted into other industries, to enter the electrical engineering industry. Such sandwich course schemes are dependent upon a large measure of co-operation from industry, as the students will need a maintenance grant or the payment of wages during each period of six months spent at a technical college.

The need for such sandwich courses giving improved training facilities to selected men from the industry-based stream has, I think, been emphasized by the authors, particularly by the conclusions given in the last paragraph of Section 5.

Turning to post-graduate evening or part-time day courses at technical colleges, the weakness mentioned under (*a*) in Section 4.2.2 may be overcome by arranging for a member of the full-time college staff to act as organizing lecturer, responsible for co-ordinating the work of the several visiting lecturers.

The interwoven series of lectures given in the Advanced Engineering Course described by the authors appear to be a most valuable form of post-graduate training, with immense possibilities. Can the authors describe the method of selection employed for entrance to the course? Is the course intended mainly or solely for those graduates likely to be engaged on research or development work?

The content of the Advanced Design Course (Section 7.3) appears at first sight to be unsuited to the needs of men with Higher National Certificates. The severely practical bias given to the lectures appears to be unnecessary for men who have presumably followed a five-year apprenticeship in the works. It may be, however, that the lectures are concerned with new developments in manufacturing techniques, rather than with standard methods. Perhaps the authors would enlarge on this point.

Mr. A. J. Coveney (*at Leeds*): There is no doubt that the burden of scientific training has been for years the responsibility of the industry, and the paper indicates the advanced nature and the costliness of such training which has been undertaken by a large manufacturing organization in the electrical industry. Will the authors express their views on the merits or otherwise of setting up a specialized National College or Institution, sponsored by the Government and supported by both the industry and the universities, to give this advanced training to the electrical engineer? Such a college has already been set up by the aeronautical industry at Cranfield, which, in addition to providing the post-graduate course, also provides the facilities for advanced technical research and training.

There has been no mention of the Faraday House student. Possibly, in view of the sandwich course, the authors would recommend a different syllabus in the scheme for these students.

With regard to interchange, I think not only should manufacturers send their senior technicians to give lectures to colleges, but also, as mentioned in Section 4.2.3 of the paper, by the lectures already given by Prof. Carter, the colleges should likewise provide certain lectures to students at manufacturers' works. I would also stress the importance of exchange of students between the manufacturing industry and the supply world and vice versa. This interchange of knowledge with the various problems and difficulties concerning each section of the work would help to solve many of the problems of to-day and to reduce some of the delays in both planning and production.

The authors refer to eight professorships and ten doctorates awarded in the last ten years to men from the industry. It would be interesting to know what sort of training these men received.

The immediate problem is no doubt the acute shortage of suitable young men. With the demand for technicians in the Armed Forces and attractive appointments in the Colonies, British industry must provide suitable and equal prospects both in advancement and money, if it intends to retain its share of these younger men, and no doubt with the rising cost of living and taxation, the financial aspect is considerable.

I would conclude by quoting the well-known old Chinese proverb:

> If you plan for one year, plant grain.
> If you plan for ten years, plant trees.
> If you plan for a hundred years, plant MEN.

Prof. A. Tustin (*at Birmingham*): There is urgent need, with no fear of surplus, for a greatly increased flow of men with the knowledge, the keenness and the personal qualities to press engineering development ahead faster. The honours degree standard, supplemented by two years of practical training, is only a beginning of the process of building up the knowledge and skill that these men require. They require, in general, more mathematics, and in particular a deep and intensive study of different sets of specialized topics close to their particular specialization. It is agreed that such men should be thrown at a very early stage into work that calls for creative and discriminative mental effort, and for the play of their highest qualities of intellect and determination.

The controversial issue that is raised is whether such men would progress better in the long run, as a first alternative, by returning to the university for one, two or three years as post-graduate students, or as a second alternative, by being employed on development work in industry for the same period. It is important to note that the period in question is most usually only one year, and only for exceptional students should two or three years be contemplated.

I suggest that both of these courses are inherently capable of giving the required result provided that certain conditions are met, and that we must change the question entirely from the

form "whether A or B" to the form "how can we make both A *and* B effective?"

I am well aware that post-graduate training in universities needs improvement; but perhaps even more so does post-graduate training current in industry. Let us find out what is wanted in both fields. In the first place, as Prof. Willis Jackson said in the discussion in London, there must be no question of doing away with research in the electrical engineering departments of the universities. Industry's first demand on the universities is for first-class undergraduate tuition. It is, in my view, essential in the long run, if we are not to see the standards of undergraduate teaching sink to squalid incompetence, that a high level of research activity should be maintained in such departments.

If research work is being properly carried out in engineering departments of the universities (and industry could and should help to see that this is the case), there is scope for training there a limited number of post-graduate students. At present, because, as the paper admits, industry is unwilling to release men to return to the universities, a very large proportion of such places as are available is being filled by foreign students, in some instances much more than 50%. Thus industry is throwing away a resource that is at its disposal.

With regard to the training that can be given to a young man in industry, the authors should make more clear whether they mean their remarks to be taken to apply only to the organizations with which they are associated, where they may be justified, or to industry as a whole, where I am sure they are not. The authors know quite well that in very many departments in many firms the real need is to get young but technically mature men into the departments who have a fresh outlook and have drunk waters of inspiration from some other fountain than the somewhat stagnant pool of the department's own inbred resources.

For most of an engineer's life, of course, his further studies must unavoidably be in parallel with his tasks of production, with the daily pressure of delivery dates, and the necessities of doing the job by the tools already to hand. The university gives a young man something else—it gives him time. Time to probe his problem to the bottom, to try unconventional approaches, to read widely rather than narrowly, to draw ideas from discussion with a great variety of persons.

To sum up, I would say that I believe the author's scheme of training within industry is of excellent intention and of great potentialities, but even in their own exceptional organization it will need immense devotion and effort to supervise it so that it will give anything like the results the authors hope for. I beg them also not to forget that, somewhat unsatisfactory as they think post-graduate training and research in the universities to be, it should be appreciated nevertheless that it is of overwhelming importance to the electrical industry that the work of university departments should be supported and strengthened, and that this requires the continued support of extra-mural research and post-graduate work. It is not at all a question of the research requirements of industry being turned over to the universities; such an idea would be ludicrous. The resources of personnel and materials of the university electrical engineering departments are trivial compared with those of the great industrial and Government research establishments. The point is quite a different one, namely that their proper—if necessarily quantitatively small proportion of the total—research effort must be maintained and fostered within the walls of the universities.

Mr. L. L. Tolley (*at Birmingham*): There is a problem which I think Prof. Tustin describes under alternatives "A" and "B," and this is a personnel problem which is not capable of a definite solution. One can quite see, as Dr. Gibbs has pointed out, that if the individual remains at the university and does not get into industry until he is about 30 years old, he gets in a way set into a groove; he has not been called upon to take responsibility for getting results, and if he does not do that until he is well on in years he may never get to exercise that responsibility. On the other hand, it is perfectly true, as Prof. Tustin has said, that to cut short the best men's post-graduate studies arbitrarily might be in certain cases a serious mistake. The problem seems to be not a question of whether it is alternative "A" or "B" in general, but for each individual, and I see no option but to suggest that the university must give the indication whether the individual is such a person as ought to go on for several years.

Prof. Tustin also referred to a point which occurred to me, that perhaps the organization with which the authors are associated has rather special conditions; it is a very large concern and it must have a large say in the technological training arrangements in Rugby. That does not apply to the same degree to firms in larger towns, nor to small firms in small towns. The Post Office is almost at the other extreme; it has a very small number of posts filled by men who might be taking post-graduate courses such as those mentioned in the paper. In Birmingham we should have perhaps six or seven, in Nottingham, Leicester and Coventry there would be only one or two, and none at all in the smaller towns. Obviously we have so few people that we cannot have the technical training establishments in the towns where the people are, and we are bound to depend upon the universities, apart from the fact that we do operate a National Training Centre for specialized courses on types of work with which the Post Office is particularly concerned. I am sorry I cannot quote comparable figures, but so far as I can remember the growth of technical staff in the Post Office has been very similar to that indicated in Fig. 1. I think the percentage quoted by Dr. Gibbs would apply fairly well to us also. I was very interested by Fig. 2. We have a somewhat similar system of grading, though not precisely comparable, since ours is a coarser grading dividing the men into five groups instead of nine. The main difference which would prevent a precise comparison is that we are really grading against "good average," which means that as the new man who comes in is not then "good average," our new man goes to the "C" end, whereas the new man in Dr. Gibbs's grading goes into "B." I wonder whether that big "pile up" in "B" consists to any major extent of the new entrants.

Mr. J. H. Patterson (*at Birmingham*): Mention was made of the "finished product." We have a training scheme, and I have consequently had fairly considerable experience as regards this "finished product"; I have been very disappointed indeed. Whenever a university graduate has been sent to me for a period of training, to learn perhaps more of the practical side than he has done hitherto, I always invite him to my office in order to outline the general run of what is intended and what we are trying to do. He is questioned to find out where his inclinations lie, and every endeavour is made to give him as much experience as possible in that direction. It seems to me that these people are "spoon fed" too much. My experience has been that they lack initiative to a very marked degree. The only man, in a matter of dozens, who showed any initiative was a Greek. He came and asked questions and I was very pleased indeed to do everything possible to put him on the right track. At the end of the period of training he was most grateful. I have found generally both a lack of initiative and inability to search round and find out information for themselves.

I think a great deal depends upon the ability of the teacher himself. The teacher and mode of teaching is of the utmost importance. A poor lecturer can spoil a good student, and conversely, a good one can produce results from an indifferent type of pupil. I suggest that more initiative should be inculcated

into the students so that it will be forthcoming as and when they go out into business.

Mr. W. H. Bell (*at Birmingham*): On this question of research, the doubt is how far people will find suitable leaders under whom to serve their research apprenticeship in industry. (It has been pointed out that the authors' organization is exceptional in this respect.) I spent a good while in industry myself and on returning to the university realized with surprise how far the standard of research in industry is liable to fall below the best quality.

It is the function of the universities to produce ideas, and not prototypes, though if some places in industry also produce ideas that is all to the good. The Percy Committee suggested that whereas our ideas are good the difficulty is in getting them put into practice. I do not see that it would help to transfer the potential source of ideas from the universities to industry, even if its fruitfulness were not diminished in the process. There might, on the other hand, be a case for a really joint effort between universities and industry by analogy with the position of the teaching hospitals in medical training. This joint effort would presumably take the form of a research institute, and the possible function of such an institute has first to be established economically as well as academically.

Given the present facilities, I think it is a fair compromise that the most promising students should do a one-year research course (e.g. the M.Sc. course which is available at a number of universities) to start their apprenticeship in research. This gives an opportunity for vocational specialization of studies and also gives the student an opportunity to exercise the initiative which the authors find so frequently lacking in first-degree students. I think such a one-year research course is the biggest contribution which the universities can make to the needs of industry at the present time, and I hope some of the graduates from such courses will eventually apply their abilities to the problems of production as well as those of developments.

Dr. E. H. Norgrove (*at Birmingham*): I like Prof. Tustin's treatment of "squalid incompetence" in teaching. I agree that research is no substitute for practical training, but under his eminent predecessor Prof. Cramp, it was possible to work on research and at the same time incorporate a good deal of practical experience.

I should like to ask who are these supermen who do the assessing in the organization we are discussing, how are they trained and who assesses them? Finally, all this talk about education and so forth has been on a very high idealistic level, but we have to remember that the man has to live his life as an individual. It is all very well to say that he must spend so many years doing this and so many years doing that, but a man wants to get married, have a home and children, and I have yet to see any reference to that in these rather grandiose educational schemes.

Mr. A. R. H. Thorne (*at Birmingham*): Little reference has been made to the financial side of training. It appears that the assessors of the usefulness of various students to industry are interested only when the fruit is ripening; what about the green state, when the students are given early training?

Those who are fortunate enough to obtain substantial financial aid are able to go to a university. There must be thousands of students who only attain Higher National Certificate standard owing to restricted financial aid, whereas help at this vital stage would enable a large proportion of them to obtain a higher standard. I am interested to know whether active steps are being taken within industry to help those students who would benefit by additional training, this help being apart from scholarship aids of the usual kind.

Mr. E. S. Hall (*at Birmingham*): Some of the views put forward have been rather weighted to suit the ideas of the authors; for instance the curve in Fig. 1 could well have been drawn as a straight line. Similarly I feel that the curve of grading of the pass-degree engineer as shown in Fig. 3 looks rather a different shape if you miss out the man who achieved Grade A+ at the age of 30. It particularly alters the line drawn at the front part of the curve. You must also remember that these points on the curves represent different engineers and not the progress of one engineer.

I should like any information the authors can give as to how these curves would look for the commercial engineer and for the engineer who takes up the manufacturing side. It has already been pointed out that we in this country do not suffer from the lack of ideas but do suffer seriously from putting these ideas into practical shape; that is where the manufacturing engineer comes into his own, and it is therefore very important to attract good men to the manufacturing side. I should like to know whether the curves for the commercial engineer and the factory engineer would differ markedly from those for the design engineer; in other words, are the same qualities and the same type of individuals required for the design engineer as for the factory engineer, and does the honours man, in general, still show up markedly superior for these applications as compared with the pass-degree and the Higher National Certificate man?

Mr. W. S. Terzi (*at Birmingham*): The authors state that when a man has completed his university course they do not consider it desirable that he should stay on for research, and when he has once gone into industry his employers are not prepared to release him or, they say, he is not prepared to leave to go back to the university, mainly for financial reasons or considerations of seniority. The question, then, is when is he going to do research if that is his wish? They have examined the problem from their angle, but they have not really looked at it from the point of view of the person concerned. We are living longer these days, why cannot we be left to enjoy our youth? Why all this concern over the age at which we achieve executive status?

Industrial and university research are usually not on the same level, nor have they had the same objectives; the former is usually a means to an end whilst the latter is an end to itself. If industry will not release men to go back to the university, it may become impossible for the staff therein to carry on research work. It is not unlikely that this may result in the university staff becoming static and unprogressive, and that with tragic consequences as Prof. Tustin has already pointed out. Such a state of affairs would also obviate the paramount factor which differentiates between the individual universities from the technical point of view, this factor being the head of the department and the various research activities in which the staff are engaged.

The suggestion made by Mr. Bell that some students be allowed to stay on for one year after graduation is excellent. As an undergraduate the student has to cover a certain curriculum; if he is allowed to stay on for one year after his finals, then notwithstanding the technical self-confidence which he would gain from such a period, the fact that he will come into direct contact with the staff in the research department may have a great influence on his future. Dr. Gibbs has said that a student may work on present-day research at the university and then take an appointment which is not at all related to that research. That may happen, but on the other hand a man's future may be changed owing to his post-graduate activities in the university—his coming into contact with a certain type of work which he may decide to continue afterwards. I think that this is a point to be emphasized.

Mr. P. A. White (*at Southampton*): As a student I find the post-graduate training scheme rather discouraging. It seems to me that anyone who wants to get on in the electrical industry is faced with many years of extremely difficult and exacting work,

in fact he is faced with the prospect of being a glorified schoolboy until the age of 35.

This prospect might discourage many students from entering the electrical industry. The scheme may well produce first-rate technical robots, but I wonder whether the authors have ever considered what type of men it will produce.

Mr. A. T. Crawford (*at Newcastle upon Tyne*): I agree with the authors on the desirability of practical training and on the undesirability of the creation of new institutions. It would appear that graduate engineers, on completion of their university training, are not particularly anxious to receive practical training on a course. They are more inclined to look solely at the immediate financial reward they can obtain for their services, and they may be offered appreciably more than would be paid to an engineer undergoing his two years' post-graduate training.

One speaker has suggested that the authors wished to eliminate research work at universities, but I do not believe this is their intention, and I consider it essential to retain research facilities at universities, with an honours school having a limited number of post-graduate students. The limited capital expenditure that can be incurred necessarily limits the useful work by post-graduate students.

The authors mention a universal figure of expansion in the industry of 4–5% relating to the technical staff necessary to maintain conditions on a satisfactory basis, and subsequently talk of engineers trained in England taking up appointments abroad. Is this figure truly universal, or is it only an average with comparatively wide variations in different countries?

I endorse whole-heartedly the sentiment that grammar schools and public schools should be convinced of the soundness of recommending some of their best men to take up electrical engineering as a profession, and the universities can assist in this by allowing their staff to teach engineering subjects in grammar schools so that the entrant from a grammar school comes with a knowledge of more than simply pure science.

Various comments have been made on the level to which mathematics is taught in different institutions, and the authors have found widely different standards in their men who should normally be at the same level. There is no suggestion that the man on the lower level could not absorb the more advanced work, and more vigorous steps should be taken to improve the level of mathematics up to the highest standards now taught in engineering courses throughout the country; I feel also that much more attention could be devoted in the earlier years to advancing the level of mathematics taught in primary and grammar schools. There would then be no need for the men in later life to spend time on further training in the subject.

On the charts shown in Fig. 3 it is not quite clear why there should be such a limited number of honours graduates after the age group of 35, and the authors say that the evidence they present may lead to erroneous deductions unless it is analysed very carefully. For those of 35 years of age and over, pre-war technical education was reasonably stable, and I thought it would have been possible to gain useful evidence from the charts. It appears, for example, that honours graduates with few exceptions have maintained their early promise in later years, whereas pass graduates have more nearly remained as average engineers.

Dr. W. J. Gibbs and **Messrs. D. Edmundson, R. G. A. Dimmick** and **G. S. C. Lucas** (*in reply*): In the discussion, university professors and other educationists have raised the question of research training in universities. We have to differentiate clearly between those men who intend to make careers in industry and those who wish to spend much of their lives in research. In general, it is undesirable for a man who seeks a career in industry to remain at the university after graduation. We agree that there are a few exceptions to this general statement. It is said that unless university staffs have post-graduate students working under them, their own research work must suffer and the teaching of undergraduates must ultimately deteriorate. We think that if the universities retain those seeking careers mainly in research plus the few exceptions cited above, they will have enough post-graduate students to prevent any deterioration in either teaching or research.

It is our experience that those who do stay at the university immediately after graduation for two years' research are not willing to follow this with an apprenticeship in industry. They expect to by-pass the practical training; they consider their two years' research as an equivalent, which it emphatically is not. With regard to the period immediately following apprenticeship, we have found that men are reluctant to return to the university at this stage because they are keen to take up an appointment either with the firm at which they were apprenticed or elsewhere. They are even more reluctant to return after some years on the staff because by then they are specialists, already immersed in their own researches, and they fail to see what benefit they would obtain by breaking into this work to return to the university.

Let us repeat that we do not ask the universities to abandon research work and that we recognize that exceptional men have to be treated as exceptions. However, it does seem undesirable for a man aiming at an industrial career to be kept, after graduation, in what is almost admitted to be the leisurely atmosphere of the university where he "has time to think." Mr. Terzi says "why cannot we be left to enjoy our youth?" We ask educationists to ponder this question and its context. We also draw attention to the contribution of Mr. White, another student, who is dismayed at the prospect of additional study in industry. No one is compelled to undertake further academic study after graduation, and many do not.

We can now deal with some of the specific questions raised. Dr. Walton raised some concerning the Advanced Engineering Course. It is intended only for those wishing to take up design or research, and the selection is made from an assessment of the work done in the preliminary course at the College of Technology and the examination that terminates it, and as a result of individual interviews. The lectures in the Advanced Design Course are concerned with special techniques and new developments.

In reply to Mr. Tolley, the engineers graded "B" form the largest group because all new entrants start with that grading. Mr. Hall suggests that Fig. 1 could have been drawn as a straight line. This is true. No set of points determines the nature of the curve to be drawn through them. We chose a compound-interest curve because the industry is expanding according to this law and it seems reasonable to suppose that the expansion of technical staff follows the same law. However, if a straight line is drawn, it reinforces our argument that a vast increase in the number of graduates in engineering is unnecessary.

Mr. Hall is right in suggesting that the curves of Figs. 2 and 3 would be a little different for commercial and factory engineers. For instance, personal qualities are of prime importance in the commercial engineer. While, therefore, the grading of honours graduates would not be markedly different, the pass men and Higher National Certificate men would tend to rise more quickly. A more important difference lies in numbers; the factory and commercial departments tend to have a smaller proportion of graduates on their staffs.

We regret that owing to space limitations we cannot discuss all the points raised, but we are very grateful to all who have taken part in the discussions and thereby given us all food for thought on this most important subject.

DISCUSSION ON

"DOMESTIC ELECTRICAL INSTALLATIONS—SOME SAFETY ASPECTS"*

SOUTHERN CENTRE, AT SOUTHAMPTON, 9TH JANUARY, 1952

Mr. H. E. White: While the sale of refrigerators has increased, I feel that the percentage of fires per refrigerator has not increased. I note that the television-set figure was 96, and although the author states that he does not know the number of increased fires at the moment, does he think that if a television transmitting station opened up in this area, television sets would be a serious source of fires?

It is the Southern Electricity Board's practice to insist on earth-leakage trips where the earth in rural areas cannot be connected to a metal water-pipe, and I am wondering what the author's views are, if we use these earth-leakage trips in a more general way as a protection against fire. In describing the lantern slide on circuit-breakers, the author stated that a certain Board did offer this together with free maintenance, but I do not think it would be a practical proposition for any Board to maintain the circuit-breakers. Perhaps I have not the true facts.

We have recently had a fire in an electric drying cabinet of a fairly well-known make. Two fires have occurred in this type, which is used in a school or hospital where towels have been put on the racks. A towel had fallen down on to the elements rated at 2 250 watts, and the terrific heat at the bottom of this cabinet caused the fire. I should like a little advice from the author on fires in drying cabinets.

Mr. H. Bateman: Domestic installations on which uncleared earth-leakage can occur constitute a danger, and, as is emphasized by the results given in Tables 3 and 4, the circumstances permitting this occurrence are all too frequent. A simple way of reducing the loop resistance and consequently the danger can often be found by the use of the service cable sheath for consumer earthing. Although it is appreciated that particularly in some of the older installations this method cannot be applied for technical reasons, approval of its use is not generally expressed by the supply authorities. Can the author say whether there is any likelihood of obtaining some general agreement with the supply authorities on this subject?

It is of interest to note from Table 5 that when improving the earth resistance of a number of installations, in order to achieve a resistance of less than 1 ohm, it was almost invariably necessary to make the connection to a water pipe. In general, then, if this method was used by consumers it would seem that any difficulty in obtaining a low earth-loop resistance would be at the supply transformer. On the other hand, it is apparent from Tables 3, 4 and 5 that it is not uncommon for water-pipe earths to be called upon to carry currents exceeding 100 amp under fault conditions, and in such cases as test No. 1 in Table 4 continuously.

Perhaps the author would be good enough to comment on the suitability of domestic water-pipes for this duty.

(The author's reply to the above discussion will be found on page 252.)

NORTH-EASTERN CENTRE, AT NEWCASTLE ON TYNE, 11TH FEBRUARY, 1952

Mr. G. W. B. Mitchell: The subject of the paper bristles with difficulties. For one thing, the available statistics are inadequate, and for that reason the interpretation of such as are available is open to argument; for another, the problem has to be considered from several angles—human, political, economic, technical and, last but not least, legal.

There would be little technical difficulty now in providing complete protection against fire and loss of life, but the cost would be great and we must not lose sight of the fact that it is our duty to provide a cheap and abundant supply of electricity. This, like any other service to the community, cannot be provided without some risk: the difficulty is to decide how much.

I do not think that the ordinary citizen is really "risk conscious," except in the abstract, and any supply authority has great difficulty in "selling" safety if the consumer knows it will cost him more than a very small sum.

There is, of course, no such thing as no risk in life, and I believe that any community which decided to subject itself to no known risks would die out pretty quickly. The avoidance of the risk of childbirth would alone see to that.

That is not to say that I do not think that very careful consideration should be given to the matter, but rather that it is difficult to maintain a proper sense of proportion and I often feel that in this country we tend to lose it in electrical matters. I would like to see the total number of fires caused by electricity, given in Table 1, related to the total number of buildings in the country. On this basis the risk is very small, otherwise insurance premiums would be much higher than they are.

Surely, before we decide to spend a lot of money in reducing electrical risks we should compare these risks with all others: risks from ordinary fires, falling downstairs, boiling fat, traffic on the roads, dogs and storms killing livestock, and a hundred others. Without this comparison we are in danger of loading one particular service with a disproportionate burden. The whole matter turns on the undefined word "reasonable."

In my view it would not be reasonable to pay more than we are now doing for domestic electrical installations, and, if possible, they should be made cheaper. If we can improve their safety without extra cost, however, by all means let us do so. The cost of maintenance of more elaborate installations would alone be important, if the elaboration were to be continuously effective.

Mr. E. C. Lennox: I agree that the figures provided in Table 1 leave "room for widest divergence of view." They are provided by Fire Brigade reports. Nevertheless the author's interest and advice on such matters is always appreciated by the industry.

The Institution's Wiring Regulations regarding earthing are limited to consumers' premises. It is not established that undertakers have responsibility to ensure a return path from a consumer's earth point on his installation to the substation transformer neutral. In high-resistivity areas, with lack of metal water-pipes, undertakers must consider multiple protective earthing. Conditions of the Ministry of Fuel and Power for multiple protective earthing are generally considered to be too arduous. Facilities provided by the undertaker who has met the additional cost of multiple protective earthing should be conditional upon relief of the undertaker from liability; for example a Post Office telephone box—no water supply available—could use instead of costly earth stakes the sheath of the supply service cable as an earth. It would seem ungracious on the part of the consumer if, as a result of using this facility and saving

* SWANN, H. W.: Paper No. 1218 U, December, 1951 (see 99, Part II, p. 255).

cost in the installation, he should place the full responsibility of earthing of the installation upon the undertaking.

Earth-leakage circuit-breakers are the alternative answer to rural electricity consumers without adequate earthing facilities. The cost may be relatively high compared to fuses, but already the cost of service to the consumer is higher than in urban areas where water-pipe earthing facilities are normally available. Earth-leakage circuit-breakers should have a much wider use, and, having regard to their cost, there should be no objection to their controlling the whole installation where, if necessary, suitable overload protection can be provided for local circuit control. Detailed instructions should be given to consumers as to method of operation and procedure in the event of operation.

Thermal protection offers considerable improvement in safety for such special applications as small motors in refrigerators, vacuum cleaners, radio circuits and so on. They should be so arranged that they can be replaced only by skilled personnel.

Mr. K. M. Mackenzie: Table 2 discloses a ratio of 2 out of every 5 buildings examined as being defective. It would be helpful if the nature of the defects could be published along with any conclusions which might throw light on the fires recorded in Table 1.

The paper refers to the difficulties encountered when inspecting and testing old installations. It is to be hoped that the National Inspection Council, if and when it begins to function, can enlist the co-operation of contractors to provide diagrams of connections and data sheets. A start could be made with new houses. As an inducement to the contractors they might also be authorized to fix an official warning label—say on the meter board—with standardized wording which might deter unqualified persons from making alterations and additions to the wiring. Public safety and business to contractors should result. Even if such notices were ignored the diagrams would, at least, assist subsequent work and inspection and testing. They will not all be lost or destroyed.

Valuable information is given in the paper about experimental load tests made to determine the risk of fire in cable runs. It would be interesting to have the author's views on the likelihood of semi-enclosed rewirable fuses starting a fire. The hot flash which occurs when these fuses blow can readily ignite inflammable material. Prevailing shortage of solid fuel has undoubtedly increased the likelihood of overloaded house wiring. Tests carried out locally demonstrate that such overloads can melt the wax or varnish out of standard types of cable insulation. This fluid runs down over the fuse and it can be ignited by the fuse blowing. Evidence from these tests is being passed on for study by the appropriate authorities. The paper quotes "tests which seem to indicate more risk at box-outlets such as connections to distribution fuse-boards." Is it probable that such risks are increased by the blowing of semi-enclosed fuses under the conditions I have described? Post War Building Studies No. 11 specifically recommends h.r.c. fuses. It is not stated whether the authors of this recommendation had fire risks in mind, in addition to other technical and commercial considerations. If cartridge fuses do reduce the fire risk, should not this fact be more widely advertised? Insurance companies might thus be persuaded to encourage their use by a lower premium. Discriminating premiums might prove to be much more effective than technical arguments about discriminating fuse characteristics. Although the financial inducement might appear to be insignificant, such a policy would exert a strong influence on future practice.

Fused plugs in outlet sockets were developed primarily for use on ring circuits although they are no doubt being installed also on radial circuits. These small quick-acting fuses can afford useful protection against faults on appliances although they are officially intended to protect the flexible cables only—see B.S. 1363. Table 1, however, discloses that by far the greater number of fires are caused by faults on the fixed wiring. I would like to know whether the author would agree that the circuit fuses—rewirable type only—are likely to be strengthened to ensure that only the plug fuses blow. This would leave the fixed wiring less well protected, and although it may result in less frequent operation they would certainly clear with more violence and flame when they did blow, and any fault developing in the fixed wiring would be more likely to persist and perhaps to build up dangerous heat at the fault.

Mr. J. Mackenzie: When the first speaker, Mr. Mitchell, referred so disparagingly to the life risk factor, I made a note "What is one life worth?" Perhaps Mr. Mitchell can let us have an electrical manufacturer's assessment.

He asks, "Are we expected to sell safety?" I say definitely, "No." It should be provided free of charge by electricity manufacturers, electricity undertakings and contractors.

I have the honour to be a Member of the Institution of Fire Engineers, but at this moment I do wish that I also had the Diploma of your Institution so that I could enter into your discussions with more confidence on technical matters.

As a layman, I feel that what is necessary is good wiring and conduits, proper fusing, well-insulated appliances, safe switches, connectors, adaptors, etc., and sound workmanship.

I can assure you that the types of fire which have been shown on the screen, caused by decrepit fuse boxes and distribution boards, faulty refrigerator motors, etc., have occurred quite recently in this city and that Mr. Swann's figures of fires resulting from electrical causes can be accepted as factual.

Portable electric fires, wireless and television sets and by no means least, refrigerators, as well as cheap and nasty wire, switches, plugs, sockets and adaptors, which are offered for sale in large emporiums at very attractive prices, all add up to a large fire-raising medium which can well result in the fire risk growing to a very serious extent.

Between 1948 and 1951 more than 10% of fires which occurred in the Newcastle and Gateshead area were caused by electrical faults and appliances.

My fire prevention officers are anxious to reduce this figure and have asked me to seek Mr. Swann's opinion on three matters which may help in achieving this object:

(1) The general suitability of polyvinyl chloride as a substitute for rubber, flexible or tough. How does it stand up to wear and tear in movement, in relation to the more usual materials used for flexible leads provided for domestic appliances?

(2) Could the use of foolproof circuit-breakers not be considered in the modern home, or alternatively, cartridge-type fuses so fitted that substitution would not be possible?

(3) As electric kettles and irons are in many cases protected by thermostats or spring-loaded plug ejectors and subject to mechanical failure, does he think that a fusible link, incorporated in the appliance, which would fuse at a predetermined temperature, would be better?

Mr. W. Cross: Many installations have been in use with satisfaction to the householder for up to 40 years or more, without a major overhaul, and it will be found that the wiring functions satisfactorily if the cable is not disturbed for alterations, additions, repairs or for inspections; accessories such as the switches, lampholders, and flexible cords will have been replaced when necessary and will therefore be in fair condition. The number of serious faults is so small that the average householder supported by the experience of his friends is not prepared to pay for a thorough inspection.

For houses I prefer wire-fuse protection to the earth-leakage protection mentioned by the author as it is not so elaborate,

requires less maintenance and inspection, is cheaper and fails to safety. The author devotes much space to the important subject of earthing, but I would appeal for a simpler approach to this as to other matters. I suggest that the supply authority should provide an earthed conductor (sometimes the cable sheathing would be suitable) connected to earth as often as possible, to which consumers' earths, water pipes, gas pipes, metal structure or buildings and all other metal should be solidly connected.

The author suggests that the neutral conductor should be connected to earth frequently, and in Section 8 he proposes to rely on the number of connections between the neutral and earth at consumers' premises. This multiple earthing of the neutral would cause this neutral to be always at earth potential and it could be used as the earthed conductor. This system would permit the use of earthed-concentric wiring which I believe is the safest of wiring.

Loop testing (Clause 7) for earthing is theoretically excellent, but I consider too elaborate (with its calculations) for routine testing of domestic installations usually with not more than 50 points.

Mr. J. N. K. Rankin: I would like to raise a point in connection with pin-grip or close-joint conduit installations.

Even if the installation is very carefully installed by a competent electrician, with all paint and enamel removed from the fittings and the conduit ends, no permanent guarantee can be given as to continuity. This applies particularly to pin-grip installations, where I would not care to give guarantee in dry situations for more than a few months, particularly in industrial areas where there is vibration.

In the case of lug-grip installations, continuity will probably be maintained for longer, provided the situation is dry. Any dampness will reduce conductivity to a very small proportion of its original figure.

Earth connections, which normally consist of an earth clip on the conduit and another on the water pipe, with a conductor of suitable size joining them, are particularly liable to failure through corrosion, and the earth clip, even though it may be carefully fitted to a lead water pipe, cannot be depended upon indefinitely; firstly, the water pipe is not truly round, and secondly, the lead under pressure tends to flow.

In a considerable number of cases of fires in domestic premises, which have been determined to be due to faults in the electrical installation, it has been found that the conduits and gas pipe were installed either in the same slot in the floor joints, or, what is worse, crossed at right angles so that there was a better chance of a point contact.

Supporting Mr. Lennox's statement regarding the provision of an earth circuit-breaker, the use of this circuit-breaker would eliminate the action taken by certain consumers who step up the fuses in the event of a fault until such times as there is visual evidence of defect by smoke, or otherwise.

I would strongly support the use of a small circuit-breaker for local circuit control. Due to the present tendency to install cartridge-type fuses in domestic installations, there is some evidence that consumers, faced with the relatively heavy cost of replacement, are re-wiring these fuses themselves. A small attractively priced non-adjustable circuit-breaker would at least prevent this.

Regarding the inspection of installations by a competent authority, while fully in agreement with the previous speaker, I am wondering how long it would take me to carry out the suggested tests on the 50 000 consumers' installations in my district.

Mr. J. S. McCulloch: Mr. Swann suggests that inspection and test of protective devices might prove more practicable than large-scale inspection and test of installations and appliances already in use. I would say that the large-scale inspection and tests of existing installations and appliances is not only impracticable but is impossible under present conditions and is likely to be so for many many years. Furthermore, automatic protective devices in the home are liable to misuse and damage. In my opinion the safety of domestic electrical installations can best be attained by ensuring that defective apparatus is not sold to the public and that wiring is installed by properly trained wiremen. Now that we have a nationalized electrical supply industry I suggest that electricity boards or the central authority should establish proving stations to which manufacturers could submit apparatus, and after they had been approved, authority be given for the manufacturers to incorporate a marking device showing approval. A high standard of wiring installations can be achieved by a system of certified wiremen. Defective appliances could then be traced to a particular manufacturer and defective installations to a certified wireman; and his certificate could be withdrawn after repeated breaches of good practice.

As a rule water undertakings do not allow equipment to be connected to their systems unless it bears their stamp of approval. I believe the Swiss electricity authorities also only allow appliances bearing an approval stamp ASEV to be connected. Electricity Boards should insist on a similar procedure. Meter readers could make occasional checks, and, as all approved apparatus would bear an official mark, they would not need any technical training to assess whether apparatus was safe or not. Furthermore, unmarked appliances would be difficult to sell.

One risk of fire damage not mentioned by Mr. Swann is the mounting of control equipment for fluorescent lamps remote from the lamps. The current-limiting feature of the choke prevents protective devices operating.

Mr. F. E. Heppenstall (*communicated*): The figures for the resistances of the loop tests shown in the paper are not unduly high for rural areas. Some tests taken in Wigtonshire some years ago showed transformer earths varying between 19 and 130 ohms before treatment. Where small village water mains were used for earthing of consumers' premises a number of tests showed that the earth resistance of these water mains varied between 1 and 6·6 ohms. I do not see any reason why the earth-leakage switch should be connected to an auxiliary electrode, as the operation of the voltage-type earth-leakage switch is the same whichever way it is connected. The only advantage I am aware of for using a main and an auxiliary electrode is in the rare occurrence of a lightning surge affecting electrical appliances in the house. Even then I do not think there should be any difficulty if the trip coil of the earth-leakage switch is wound with heavy gauge wire.

The question whether the domestic installation should be separated and more than one earth-leakage switch used is largely a matter of first cost and the type of maintenance given in rural areas. This question might usefully be put to the Electrical Association for Women.

Mr. H. D. Phelps also contributed to the discussion at Newcastle upon Tyne.

[The author's reply to the above discussion will be found on page 252.]

EAST MIDLAND CENTRE, AT DERBY, 12TH FEBRUARY, 1952

Mr. H. L. Jones: For many years I have been closely concerned with the safety aspect of electrical installations, and at recurring intervals when studying newly issued regulations or reading installation inspection reports, I have despaired of ever finding even one installation that was sufficiently up to date to be considered safe.

Such a fit of despondency descended upon me when I first saw the statistics in Section 2 of Mr. Swann's paper. However, in the

past, optimism has usually come to my rescue, and when I look around to-night I see there are still a few who have survived unscorched the flames of electric fires.

Possibly the figures quoted in Section 2 first led me to believe the fires all occurred in domestic premises. Examination of the figures reveals that the total of 42 792 fires attended by the fire services in the United Kingdom in 1949 caused estimated damage of £467 per fire, and in the same year 7 228 fires thought to have been caused by electricity cost an average of £451 per fire. Perhaps the author will confirm that these figures include all fires, not just fires on domestic premises.

If my surmise is correct then I am not greatly concerned about the proportionately high figure of 2 250 fires believed to have been started in wire and cable.

I am, however, interested to know whether the footnote to Table 1 implies there would be fewer fires if we abolished fixed wiring and relied exclusively on flexible.

The author states that the proportion of defective installations indicated in Table 2 is not reassuring, but unless the degree of defect is studied no useful conclusion can be drawn, for he is a poor installation inspector who cannot find something wrong with an old installation.

Referring back to Table 1, we see over 700 fires attributed to cookers, presumably electric cookers. Now the usual complaint concerning electric cookers is that they do not get hot enough to cook. Such complaints only occur when the cooker is defective.

I can only suppose that the cooker fires in Table 1 were due to leakage currents referred to later in the paper.

The author invites opinions concerning the fire risk incurred by old installations. I believe age has no bearing on the risk: a good installation will remain good indefinitely, and I have heard of a great number of fires in post-war pre-fabricated houses.

The author's reference to Electricity Supply Regulation 26 gives me the opportunity of inquiring whether this particular regulation could be applied to an installation already connected. The regulation prohibits the Area Board from connecting when leakage would result, but does not mention disconnecting, and Regulation 32, although permissive, does not in practice ensure disconnection where leakage exists.

The overload tests described in Section 5 seem to indicate that the B.S. current rating for v.r. cable is unnecessarily conservative. If 12 times the rated current does not cause fire surely twice the rated current (where voltage drop is not involved) would mean the cable was "reasonably sufficient in size to prevent danger."

I agree that some fire risk is incurred by leakage to compo gas pipes, particularly leakage from earth-continuity conductors, which does not necessarily mean the resistance of the continuity circuit to earth is high. Sufficient leakage may be transferred to the gas pipe to cause melting at a point of contact with the earth-continuity conductor, and escaping gas is then ignited which soon causes rapid spread of fire.

As an electrical engineer I deplore the use of compo gas pipes, especially when they are charged with gas.

This risk can be partly removed by using covered earth-continuity conductors, and of course should be eliminated by the installation of a differential-current circuit-breaker described in the paper.

The use of such breakers would of course prevent earth leakage troubles entirely, although it would not clear phase-to-neutral faults unless and until they broke down to earth. The cost both of installation and maintenance would be an important factor, especially because reliability must be assessed, and I think it would be desirable to split even the smallest installation into at least two circuits each protected by a separate breaker, to ensure operation did not indicate failure of supply.

The time delay suggested by the author would sacrifice the most valuable feature of protection against shock.

The use of temperature-operated protective devices has certainly reduced fire risks, but these are not 100% reliable and like all protective devices are often tampered with or short-circuited by the handyman.

Finally, I would suggest that we ought to consider whether it would not be wiser to adopt a form of insulation and covering for all wires and cables that will not maintain a flame. Even where the cause of fire is not electrical, cable coverings whether new or old which will maintain a flame can assist a fire to spread very quickly.

Mr. H. A. C. Smith: Briefly, I feel that this subject falls under three separate headings, although they are all interwoven—namely (*a*) education, (*b*) legislation, and (*c*) co-operation.

First of all, education of the public. They are already educated in a particular sense so that they can mess about with electrical wiring which may have been admirably installed by a competent electrical engineer, but I do not think they are sufficiently educated to prevent them, for example, adding appliances and equipment, altering points to fit a particular plug or switch and so, as we so frequently find, causing fires. Whether it is the responsibility of the electrical supplier or an Institution of this description to further educate the public, I leave to the meeting to decide.

With regard to legislation, sometimes it amazes me to think that people, manufacturers, individuals can put on the market equipment which to say the least is lethal. I refer, for example, to a device for airing babies' napkins; no thermostat was fitted and the consequence was that as soon as it was used, it was fired or caused a fire. Whether again this Institution could cause sufficient stir to bring about an alteration in our legislation to prevent such occurrences, I do not know, but in any case, I do suggest that the suppliers of electricity should also have some say in the matter.

With regard to co-operation, I am amazed that there is not more co-operation between manufacturers, suppliers, consumers, and another body whom I am always trying to bring in where fires are concerned, namely the insurance company.

It seems that an insurance company is quite satisfied provided that somebody pays a premium to keep on insuring premises irrespective of what is going on inside them. I know that it is difficult for representatives of industries and of suppliers to get inside the houses, but I do suggest that it is not difficult for people who are insuring property to get inside them, and yet still we find that premises carrying considerable quantities of electrical equipment are inadequately protected.

Mr. J. Ross: Most electricians are aware of the necessity of earthing, but many of them do not appreciate that the resistance of the fault current loop is important. This state of affairs may be due to the fact that instruments for testing resistance are not generally available and those that can be obtained are expensive and too bulky for the electrician's tool bag.

Some years ago, Mr. T. C. Gilbert recommended a piece of apparatus which by reason of its simplicity and compactness would seem to solve the problem. It consists of a voltmeter shunted by a 100-ohm resistance with a switch in series. The phase-to-earth voltage is first recorded and then a second voltage reading is taken with the resistance switched in. The difference between these two readings is proportional to the resistance of the fault current loop. It would appear to be a fairly simple matter to calibrate the voltmeter in ohms and thus provide a cheap and compact resistance recorder which might become as ubiquitous as the electrician's test lamp.

I should like to ask the author whether he has had any experience of such an instrument.

Mr. J. N. Robertson: With regard to the installation of a safety device in the consumer's premises which would operate automatically if conditions demanded it, the first thing a consumer would do would be to find out how it worked. We have had a lot of experience with a similar type of apparatus in this coalfield area.

I think the biggest danger, as the Fire Officer mentioned, is for the consumer to add to the installation without sufficient knowledge. I imagine that more than 50% of all the fires are caused through this reason. There are some dreadful fires caused by consumers adding to the installations themselves. We suffer from that a good deal in this area, which is a highly industrialized one, and in a coalfield where there are a number of colliery electricians, but wiring a pit and wiring a house are two different matters. In any area there are bad patches where earthing is extremely difficult, and such an area is North Derbyshire.

Mr. E. R. Ashill and **Mr. M. Wadeson** also contributed to the discussion at Derby.

[The author's reply to the above discussion will be found on page 252.]

SOUTH MIDLAND CENTRE, AT BIRMINGHAM, 3RD MARCH, 1952

Mr. H. J. Gibson: The paper contains some very useful information and suggestions, but it might first be as well to get the problem we are considering in better perspective.

Even without the reservation that the figures in Table 1 include cases not due to electrical defects in appliances, the total number of fires recorded is only 0·06% of the 13 million or so installations in the country, and those attributed to wires and cable only 0·02%.

In the past there has been too much uncontrolled and uninformed publicity on the dangers of electricity. If the relative risks are reviewed dispassionately, electricity is the safest service in the home and factory, and whilst proper advice should be given to consumers, it should be done in a way that does not alarm the public.

Mr. W. R. Cox: The information given in Table 1 of the paper will have made a number of us revise the picture formed in our own minds relating to the frequency of occurrence and the causes of electrical fires in domestic installations. That electricity accounts for 16% of the total number of fires does not seem to be unreasonable, especially when it is remembered that the first use of electricity in a house is to replace candles and lamps, which were responsible for a good many curtain fires and the like.

A further examination of the statistics given show that the total number of cable fires is irregular from year to year, but that the increasing tendency is slower than the other increases recorded. This seems to indicate that the increase in fires from electrical causes is due more to the increased number and variety of pieces of electrical apparatus used rather than to an increased number of faults due to ageing installations.

On the other hand, it is obvious that the great majority of installations made up to date will have a life appreciably shorter than the buildings of which they form a part. This problem is going to be a difficult one to tackle and will probably mean additional regulations which are bound to be unpopular and therefore difficult to enforce. The author suggests two lines of approach, and a third might be the loading of the fire insurance premium on a graded scale based on the age of the installation.

It is interesting to see from Table 5 how—in some cases—the resistance to earth can be reduced, but it would be interesting to know how long such improvement persists.

Mr. J. R. Anderson: I think many faults with wiring are due to over-heating caused by bad contacts. I shall be very interested to know whether any experiments have been carried out to determine whether bad contacts arise due to fatigue of the material. This might be either the copper conductor or brass pinch screws where these are responsible for the contact. It seems possible, owing to variation in loading and consequent heating cycles, that there may be fatigue which would eventually cause bad contact and give trouble at these points.

Mention is made of bonding to water pipes, and I think we must be very careful because, quite apart from the use of non-conducting water pipes, some water undertakings, as a matter of practice, principle or habit, remove earth connections when they carry out repairs. Periodic inspections may give a false sense of security, since subsequent removal of the earth connection by the water undertaking may make a perfectly good installation quite dangerous.

Mention is made in Section 8 of uncleared earth-leakage faults. In the case of a poor or faulty earth connection, a piece of apparatus such as a convector may become "alive" and a source of danger if the thermostat is connected in the neutral as is permissible.

Figures have been given relating to the causes of fires in buildings. I should like to know whether the author can indicate what proportion of these has been due to misuse of the apparatus listed.

Mr. G. Palfrey: With regard to the necessity, or otherwise, of making a test on the older installations, my experience has been that you may have an old house which has been used by a comparatively small number of people and the electrical installation in it is 20–30 years old; it is taken over by a large corporation or used for flats, etc., and the use of that installation is very much extended. The load it carries is greatly increased, and I feel that it is very necessary to test old installations whether it interferes seriously with the terminal connections or not.

Mr. G. S. Cattell: On the subject of electric fires and radiators, something might be gained by looking back. The first red-hot wire elements were made about forty years ago. Before then we were accustomed to lamp radiators, which were unlikely to cause ignition by accidental contact. This very fact may have left the impression in the minds of users that electric radiators or fires are "safer" than other fires.

Nevertheless the earliest red-hot wire radiators were fitted with guards, only to be discarded after the First World War, when many new firms began manufacturing domestic appliances and cheapness became the order of the day. Purchase prices fell from pounds to shillings.

At this time, however, the Admiralty and shipbuilders continued to specify guards for fires, but in domestic apparatus they were becoming conspicuous by their absence. The growth in accidents over the last thirty years makes the need for guards obvious, and fortunately the B.S.I. has now specified safety requirements. Mr. Swann's paper will have proved of inestimable value if it leads to a crusade against the manufacture of unsafe appliances.

Mr. J. W. Bunting: I was very interested to hear of the development of a domestic earth-leakage circuit-breaker having a differential feature, but I wondered whether Mr. Swann, in his paper, did full justice to the ordinary voltage-operated type. He said, for instance, that where the supply was taken from a pole-mounted transformer having appreciable resistance between its neutral and earth there would be little voltage rise, under earth fault conditions, on a well-earthed piece of consumer's equipment, and he went on to say that in such cases there would be little chance of a voltage-operated circuit-breaker operating to disconnect the fault. Surely, however, if such a trip were used its relatively high-impedance coil would be inserted into the earth

connection at the consumer's premises and this would alter the distribution of voltage throughout the fault path; a very considerable proportion of the fault voltage would now appear across its terminals and one would expect it to trip very rapidly.

Dr. W. G. Thompson: I have noticed at meetings on one or two occasions that it is assumed that the water pipe is a good earth. This is not the case in rural districts. There are many farms where water is pumped up over and into a water tank which is supported on wooden beams but not connected to the feed pipe; the domestic supply is taken from this tank and there is no connection to earth whatever.

Mr. T. G. P. Nettleship: In reply to the author's request that opinions be expressed as to whether electric blankets of the high- or low-voltage type were to be preferred from the aspect of safety, I would like to suggest that the low-voltage type is preferable. In this type the insulation between the supply mains and the user of the blanket is essentially that between the windings of the step-down transformers used. The insulation is therefore in a position where it can be made adequate under controlled conditions and be easily checked. This type of blanket has a heating element of a larger cross-section than that of the high-voltage type, and is therefore more robust. It may, if desired, be earthed. The inclusion of a thermostat in the body of the blanket does not afford the high degree of safety that their use suggests. They are often so positioned as not to be in circuit when parts of the heating element touch and produce a short-circuit. I know of a high-voltage blanket which caught fire in the bed due to this cause.

Mr. G. S. Buckingham: I think we would like the author in his reply to this discussion to give us some additional information about the installation tests which he describes in Table 2. Could it be, for instance, that the defects which have come to light are the result of amateur wiring by the householder after the original wiring was put in? Or are they at the socket outlet or switch points, or ceiling roses? If so, it might be possible to bring an installation to a better state merely by changing some of the accessories instead of rewiring the whole house.

If earth-leakage trips are installed, I think it is absolutely essential that they should not control the lighting circuits. It is the custom in this area for most domestic wiring installations to be done in t.r.s. cable, and in rural installations the earth-leakage trip is put on the cooker and water-heating apparatus, not on the lighting circuits.

Mr. J. E. Boul: I was rather surprised that so little has been said about the necessity for periodic inspection of the earth connection to the apparatus. I have in mind a case where the manufacturer took every reasonable precaution to make a good earth connection from a cooker hotplate to the earth pin by providing a rustless steel wire brazed to the underside of the cast-iron hotplate. In time, after a few saucepans had boiled over, the hotplate rusted and we were then left with the earth wire attached to a piece of rust in free air and that was only found by getting a shock from a saucepan. I feel that, as time goes on, the necessity for examination of earth connections is as vital as the examination of the wiring.

Messrs. G. Goodman and **H. B. Mellor** and **Dr. E. Friedlander** also contributed to the discussion at Birmingham.

[The author's reply to the above discussion will be found on page 252.]

NORTH-WESTERN CENTRE, AT MANCHESTER, 1ST APRIL, 1952

Mr. O. Howarth: Table 1 is very interesting, but one's curiosity tempts one to inquire how many of the cooker fires or radiator fires are due to its being a heating appliance rather than an electrical appliance. When a fire has occurred it must be extremely difficult to determine whether the state of the wire caused the fire or whether the fire caused the state of the wire, and there may be a tendency when in doubt to blame electricity. Can the author tell us how reliable the figures for wire and cable are?

I note that electrically caused fires constitute about $16\frac{1}{2}\%$ of the total during the last three years covered by Table 1. In view of the expanding use of electricity, and particularly in view of the probable greater incidence of amateur extensions to installations, I suggest that the last three years' figures show that on the whole we are gaining in our measures to combat the risk. Supply engineers have ample evidence that the risk of a fatal electric shock is greatly enhanced when wiring is done by inexperienced and unqualified people.

We have had recent vivid examples of this in the North Western Area during the last few months. An instance was the sale of pig farrowing lamps to farmers. The lamps have a concentric cap, and some traders sold them with lampholders which did not adequately shield the cap of the lamp. The farmers or their employees rigged up the lamps using a lampholder adaptor from an ordinary bayonet fitting to supply them and in some cases there was exposed brass which was alive at 240 volts to earth. One fatal accident occurred, and in conjunction with the National Farmers' Union we managed to get a Press and B.B.C. warning and the Board took steps to inspect all known installations of this kind. Quite a number of dangerous installations were discovered and the farmers warned and advised as to the remedy. Work of this kind costs the North Western Board a considerable amount of money.

It would need an army of inspectors continually going round to all installations to avoid dangerous additions by unqualified wiremen. It is interesting to note what happens when the supply undertaking does take action. It has recently come to my notice that, as a result of an inspection made every time the North Western Board deliver an appliance, consumers have ceased to buy from the Board but purchase appliances elsewhere in order that they may not suffer expense resulting from an inspection of their installations.

The author has referred to earth-fault currents and given some very interesting data in Table 4. There is no doubt that the more solid the connection can be made between the neutral of the transformer and the framework of consumers' appliances the less is the risk of a fault not being cleared.

Mr. J. N. Whitfield: The greatest danger of fire due to electrical installations is, I feel, caused by bad contacts and the subsequent overheating which usually takes place at joint boxes, fuse boards and switch-fuses. It is for this reason, in my opinion, where lead-covered and t.r.s. cables are employed in domestic installations, and run under floor boards and in roof areas, that single cables should be used on the loop-in system and not twin and 3-core cables with their associated joint boxes. Single-nail buckle clips also constitute positions at which faults occur and therefore trouble due to overheating and fire risk—a danger which can be overcome by the use of a saddle in the form of a bridge with two nails, one on either side.

Mr. W. E. Swale: The many interesting technical points raised by the author are timely; but he rather side-steps the important issue of the relative responsibility of the contractor, supply authority and consumer. For instance, referring to the use of non-conducting water pipes, one large authority clearly recognizes its obligations and has been carrying out a systematic earthing and bonding operation in the case of hired appliances installed before 1935. Many thousands of installations have still to be

inspected, and one would like to ask the author where, in his opinion, such obligation ends.

The practice adopted in Switzerland of testing every domestic installation every seven years is obviously ideal and may well cost less than the estimated financial loss by fires attributed to electrical causes.

In a Sub-Area in the North West containing 380 000 consumers, one may assume that 84 000 existing installations are more than 20 years old. It is reasonable to assume that by appointing 20 additional inspectors, it might be possible to test these 84 000 installations in a period of 5 years, but that would by no means solve the problem. All supply authorities will carry out periodic tests at the request of, and at the cost of, the consumer, but the number of requests for this service is infinitesimal. The usual excuse for testing existing installations is change of tenancy, the incidence of which is such that many installations never get visited whilst others are inspected much more frequently than once in 20 years.

Mr. S. R. Mellonie: The magnitude of the difficulties involved in providing safety in domestic installations may be visualized by considering such an installation in a fifth floor flat, a farm housed on a rock foundation or a row of the older type of terraced houses fed from an underground network of cables without a lead sheath. Such conditions still survive in parts of the older undertakings.

The author devotes much attention to the fire risk, and following a series of fires in this area careful tests were made to simulate the conditions with a view to ascertaining the origin of such fires. However, in spite of full-scale tests involving ample power from a 1 000kVA transformer and prospective currents of between 400 and 800amp, it was found impossible to start a fire by blowing open-type fuses touching v.r. cables or to maintain an arc.

It would appear that the most probable cause is overheating of contacts. The action is cumulative and is aggravated by oxidation and the cycle of expansion and contraction due to switching on and off of the load. Such action might well take months and even years to set up conditions leading to a fire.

Again, cases of fault conditions resulting in the melting of gas pipes and ignition of the gas are far too frequent, and it must be regarded as a serious defect in layout to allow gas pipes and electrical circuits to be in the same channel.

In Section 8 the author visualizes the possibility that the 60amp domestic fuse of to-day may be 200amp in 10 years' time. This is doubtful because it implies an increase in power station output which it would be impossible to achieve in the time, quite apart from the fact that the majority of domestic consumers would not be able to afford the electricity bills involved.

Mr. W. F. Jarvis: I want to dwell for a few minutes on the safety, or otherwise, of harness or octopus wiring systems installed in prefabricated bungalows, because in the last twelve months these bungalows have been very much in the news, particularly in Manchester.

There are over 3 000 prefabricated temporary bungalows in Manchester, and despite all the recent publicity regarding fires, culminating in questions being asked in the House, I am happy to say that from information available the fire risk for these temporary bungalows is slightly lower than in permanent types of dwellings.

We must remember that these bungalows were originally designed for a life of five years, later increased to ten, and no doubt this influenced the committee who decided upon the type of wiring to be installed. There were a number of novel and at the same time disturbing features about the installations.

One was the omission of a main switch and fuse unit at the meter position. The v.r. or p.v.c. cables from the supply authorities' cut-outs in the hall to the main panel in the kitchen are approximately 15ft long. A number of faults to earth have developed and in some cases have melted the sheet-steel or zinc-alloy pressings used to support switches and circuit fuses, without the main fuse operating. This is perhaps understandable when one realizes that the main fuse is of the h.r.c. type rated at 60amp with a fusing factor of 1·6. What are the author's views on this point?

In theory, the prefabrication of wiring systems appears to have many advantages, but these advantages have been nullified in practice by careless installation, often by unskilled labour, or by skilled men in trades other than electricians. Again, a lot of single-conductor cables have been used with pinching screw-type terminals—to my mind a weakness in a number of electrical accessories. Moreover, this type of terminal is frequently fitted in awkward positions which makes adjustment very difficult. Prefabricated bungalows built on sub-standard sites are often subject to much more severe vibration than permanent houses. With the pinching-type terminals loose connections occur, with inevitable over-heating and the possibility of fire.

Owing to the number of fires which had occurred in temporary bungalows up to 1949, it was decided that the North Western Electricity Board should carry out an inspection of certain parts of the electrical installation in each one. We made 749 adjustments, including refitting cables into terminals in control units, replacing faulty socket-outlets, ceiling roses and switches, the faults often being due to tracking.

In 42% of the bungalows we found appliances inefficiently earthed; 18% of control panels (which are mounted in the kitchens) required some service; and 142 consumers' own portable appliances were found to be connected wrongly, that is the earth and the neutral conductors were crossed at the plug top.

Dead mice were found in 30 control panels, having apparently gained access through cable ducts, the ports in the control panels having been left unsealed.

Earth continuity between the earth pins of socket-outlets and the main earth on the cable sheath were found broken in a number of instances due to corrosion caused by excessive condensation.

Condensation has proved, and is still proving a very grave problem in these prefabricated bungalows. We have had innumerable examples of plastic switches, connectors and fuse holders tracking, which if not discovered in time might have resulted in fires.

Mr. A. Stewart: Whilst the loop-test instrument will certainly give a little more information than that normally obtained by installation inspectors, I feel there is a danger that too much reliance may be placed on the results obtained. The instrument illustrated is described as being capable of injecting a current of up to 8 amp and, on the basis of this, the current-carrying capacity of the earth-return circuit is assessed. I would be very reluctant to accept the high current-carrying capacity such as is indicated on some of the tests, Tables 3 and 4, on the basis of passing 8 amp by means of the loop-testing equipment.

The combined differential-current and voltage-operated circuit-breaker is an interesting development, and I would inquire what the losses are likely to be with this type of instrument. Presumably they would fall on the consumer and would thus increase the sales of electricity by the Electricity Boards.

One of the major difficulties in applying the ordinary earth-leakage trip to installations is to avoid the possibility of parallel earth paths, such as exist in a water-heating installation or where a small domestic pump is installed, and it would seem that the combined differential current breaker will suffer from the same disadvantages if earth-leakage protection is universally adopted.

In East Anglia, for a number of years before the war, we made

it a practice to fit earth-leakage trips on cooker and socket outlet circuits where the earth conditions were not satisfactory and left the lighting, which was carried out in t.r.s. cables with shock-proof accessories protected only by fuses. It can be extremely disconcerting if a saucepan boils over on a grill boiler and puts the complete household into darkness.

We also found a certain amount of difficulty with new solid hot plates and with the radiant-type plate, which appeared to be slightly hygroscopic. For these reasons, we found it desirable to place the earth-leakage switch adjacent to the cooker rather than send the harassed housewife running upstairs or into the cupboard under the stairs each time the trip operated. We also encouraged the consumer to operate the test button occasionally and found that they were much more likely to do this when the trip was in full view.

Referring to the faults in radio sets, there is one type of set which is especially dangerous, namely the type which uses an external resistance lead. Normally this lead operates at a fairly high temperature and, in the event of a fault on the radio set, rapidly reaches a condition when it will be hot enough to ignite clothing, carpets, etc. Having seen two or three cases when minor fires have occurred by reason of such failures, I feel that this type of lead should be regarded as dangerous and appropriate steps taken to forbid its use.

Mr. E. Roscoe: The author has said that electrically the factory is a safer place than the home. This may be a general statement or an accurate statistical statement; if the latter is the case then it is essential that some action should be taken in the near future to reverse this position.

One possible reason for this is the difference in authority between the Electricity Board's installation inspectors and the factory inspectors employed under the author. When the factory inspector calls to see the factory owner on some point of electrical safety, he is in a position to give instructions that the defect shall be remedied and he has the power of the law to enforce this if it is not done. In consequence there is little or no delay on the part of the factory owner to correct any faults on the electrical installation to which his attention is drawn. The situation is vastly different with the Electricity Board's inspectors; they have to go "cap in hand" and are often referred to as "snoopers," and on some occasions are instructed to connect the installation and to get out of the premises as they have no authority to enforce the regulations recommended by The Institution of Electrical Engineers for the electrical equipment of buildings. Until these regulations are made statutory, Mr. Swann's paper is mainly of academic interest.

I think the time has come when a standard form for installation inspection covering domestic premises should be compiled on a national basis.

I think there is far too great a tendency to believe in earth connections rather than a higher standard of insulation. It would be far better in the case of earth-free situations or situations that are practically earth free to depend on insulation rather than on earthing. For example, portable electric tools are often operated from a 230–110-volt transformer with the centre point earthed. It is my opinion that a greater measure of safety would be achieved if the centre point was not earthed, but it might be advisable to put a neon indicating lamp between the centre point and earth to indicate when there was an earth on either pole of the secondary of the transformer.

Dr. R. Cooke also contributed to the discussion at Manchester.

[The author's reply to the above discussion will be found on page 252.]

SOUTH-WESTERN SUB-CENTRE, AT ST. AUSTELL, 21ST MAY, 1952

Mr. J. H. Phillips: Mr. L. Gosland in his paper read before the Supply Section, "The Cost and Efficiency of Earthing on Low- and Medium-Voltage Overhead Line Systems," compared the cost and risk factors of a number of different methods of achieving earth-leakage protection and in conclusion provided arguments in favour of protective multiple earthing rather than earth-leakage circuit-breakers.

I have always considered that a form of current-balanced leakage protection was the answer to earth-leakage problems for both urban and rural areas, and put forward as the reason for the dislike of any form of relay protection the fact that it was the custom in this area for meter readers to test such protection at least four times a year, whereas no tests are made of direct earthing and protective multiple earthing has not been applied on a large enough scale to discover any operating weakness.

Mr. Swann has asked for comments on the use of both voltage-operated earth-leakage circuit-breakers and direct earthing on the same system; my own experience is that it has often been found necessary to erect 150 yd of overhead conductor to provide a connection to earth for the earth-leakage circuit-breaker, such connection being outside the earth field of private water supply systems in rural areas, these systems providing a direct connection with earth via water heaters, etc.

A very good example of this problem was found when it was discovered that an earth fault in one consumer's premises caused the earth-leakage circuit-breaker to operate in the next-door house due to the suction pipes of both pumping installations being inserted in a common well.

Mr. A. H. Warren: The author has suggested that the large number of earth-leakage trips now in use is an indication that they provide a reasonably satisfactory solution to the earthing problem of domestic installations as against protective multiple earthing. Surely the real reason is that until recently the regulations governing protective multiple earthing were so crippling in cost of installation as to preclude its general use. The revised regulations present a very different picture and will often provide a better and more economical solution.

Our experience on the maintenance costs of protective multiple earthing are somewhat limited for the above reasons, but I would suggest that if the alternative is between a current-balance protective circuit-breaker installed in all premises and protective multiple earthing, then in rural areas protective multiple earthing will usually compare favourably for both initial cost and maintenance costs.

Mr. W. J. Guscott: The organization of the Supply Boards is already so geared that the cost of maintenance in the strict sense of the word is of secondary importance to charges on the capital involved. Each consumer's installation is already visited frequently and continuously for meter reading and other purposes, and testing of earth-leakage protective gear should not prove a very serious additional burden. Similarly, the engineers are always concerned with routine maintenance, particularly all substation earths and maintenance of protective multiple earthing systems, so this need not be regarded as serious from the point of view of additional cost.

Investment in capital equipment demands a return by way of sales of electricity of the order of about 30% according to the characteristics of the area. Presumably the combined differential current/voltage circuit-breaker shown in Fig. 5 of the paper could not be produced and fitted under the best possible conditions for less than £10. Taking the overall capital charges at 30%, the

annual cost would be of the order of about £3. Where is this to be found? Electricity Boards are commercial organizations, and it must be realized that whatever protective methods are adopted no additional electricity will be consumed. Already the high capital charges, particularly for housing estates, make it difficult for such business to pay its way, and further costs for protective equipment on consumers' premises would only add to the difficulty unless the consumer—who must pay in the long run—is prepared to pay for additional safety through the medium of higher tariffs. This matter of costs and charges in relation to revenue return will be particularly acute in areas where the domestic consumer predominates.

Messrs. A. J. Ramsay and **L. Locker** also contributed to the discussion at St. Austell.

[The author's reply to the above discussion will be found on page 252.]

NORTH MIDLAND UTILIZATION GROUP, AT LEEDS, 21ST OCTOBER, 1952

Mr. E. Bramald: I was interested in the Table showing a record of tests on installations 30–40 years old, and the incidence of 40% faults is alarming. In my experience I have found a smaller percentage than this, but the defects are mainly due to faulty workmanship carried out subsequent to the initial installation.

I think a possible solution to the replacement of these ageing installations could be through the insurance companies offering reduced rates for fire insurance following the re-wiring of the premises and on the production of a certificate to this effect.

Regarding fault currents which are run to earth, these are very readily dealt with in an urban area such as Leeds. In general, Supply Boards are to some extent bringing relief to the contracting side of the industry by granting permission to use the supply cable sheath as an earth electrode, provided, of course, that some form of indemnity is received before use is made of that earth.

To some extent, this situation has been brought about by the advent of non-metallic water mains, but I agree that there is some justification for the development of a form of protection based on the core balance principle, particularly where fault currents are reduced owing to resistance in the earth-return circuit.

I remember one case where hot water was emitted from a cold water tap. A cooker had recently been installed and had been "earthed" to a draw pipe leading from a well. This pipe was merely hanging over the edge of the well, the end dipping into the water and the leakage current to earth had heated the water electrode boiler fashion. The water had been pumped into the tank in the roof from where it gravitated to the cold taps. Fortunately, no one received a severe shock, but the mystery remained as no faulty installation could be found. It was, however, recorded that the wiring for lighting, etc., comprised ordinary v.r. cables which were fastened to the walls and buried direct in the plaster, and were supported in the false roof by means of iron staples driven in the sides of the joists.

Mr. E. Ellis: On the question of earthing, I am of the opinion that in rural and other areas where earthing facilities are indifferent solid earthing should be installed, for the cost per consumer of an aerial earth wire is not excessive when related to the total cost of providing supply having regard to the increased safety factor obtained. This method would eliminate most of the difficulties now experienced in obtaining satisfactory earth-leakage protection.

Mr. C. E. Laybourn: We are stressing the need for fireguards on all types of equipment, particularly electrical, and also on the dangers of employing a handyman to do any electrical repairs.

Mr. Swann referred to the Fire Guards Act. This does not cover the many appliances which are already in use and which will not be affected by that law. There has recently been published a Report by the Department of Scientific and Industrial Research in which it is stated that over 7 000 fires were caused in a year due to electric appliances. We are stressing the need for non-inflammable material and the avoidance of flannelette in children's clothing. The best type of control for these risks obviously is to put a guard on the equipment. The report does show the need for more and more educational propaganda for the general public to make them aware of the dangers of electricity, which must be treated with every respect.

Mr. H. Lloyd: Mr. Swann's remarks as to the permissible earth resistance to ensure the blowing of fuses seems to relate to open-wire fuses. The modern h.r.c. fuse with twice its rated current will blow in one minute, during which time a fire could be started; with four times the rated current, the fuse will blow in one second and this should be aimed at. If isolated earth electrodes are used, to allow for seasonal variations which may result in doubling the minimum resistance, a factor of safety of two should be applied, which means that the resistance of the earth circuit should be such that eight times the rated current of the largest fuse can be passed. This is generally economically impracticable, and I have long been of the opinion that nothing less than a solid metallic connection, provided by the sheath of a cable system, or a system of metallic water pipes paralleling an underground cable system, is satisfactory.

I was very pleased to note the stress laid by Mr. Swann on the measurement of the loop resistance as I have been advocating this for years. A magneto-driven instrument is available, and whilst these may be too expensive for the small contractor to carry, they should invariably be used by the supply authority in the course of the pre-connection test.

Earth-leakage trips seem to provide the complete answer but they are subject to snags. They are delicate and the operating forces to comply with B.S. 842 are small.

The devices must be cheap and must compete in performance with protection relays costing 15 to 20 times as much. My own view is that B.S. 842 is much too onerous, and a much more robust device with a current coil in series with the earth connection operating at, say, 1 or 2 amp instantaneously should meet the case. The operation of a fuse will often be accompanied by a momentary rise in voltage on an unearthed appliance, considerably in excess of 40 volts.

Fortuitous earth connections to gas pipes, water pipes, etc., can be avoided by the use of an insulated wiring system with an included earth wire. Such systems have the advantage over metalclad that they do not spread the effects of a leakage all over the premises in the event of a fault.

Mr. F. Newey: In the table of burns due to contact, there is no statement as to the number of cases of gas or electrical fires.

Referring to fires in television sets, we find regulations imposed by H.M. Factory Inspectors for high-voltage installations in factories, yet we take high voltage into our homes. It speaks well for the manufacturers that their appliances are so reliable.

I was pleased to hear Mr. Swann's optimistic note about the future and his estimate that the current in the home may be 200 amp.

Mr. H. Moss: In 1928 and onwards I wrote a number of articles for the electrical Press with many illustrations depicting the rotten and disreputable wiring done throughout the land, and those are the kind of things that create fire risks.

I carried out a lead-covered job—a good job—and it had been

inspected and passed by the respective engineers and was put into commission. I heard later that there had been a fire at the house. They had still in use a gas pipe which ran across the living room, and the residents decided after I left the job that they would like an extra point so as to be able to use an electric iron. They engaged a handyman who said he could do the work more cheaply. He ran a single lead-covered wire parallel with the gas pipe, in contact with it, and connected it behind the fuseboard, the lead covering on to the live side. The gas pipe melted and the house was set on fire; fortunately the fire was noticed in time.

On the 2nd October, 1952, a girl of 14 years of age, in Surrey, was having a bath. She reached out of the bath to take a towel from the towel rail and was killed. I was particularly interested, and tried to get to the bottom of the trouble, and received every assistance from the Press and the Electrical Contractors Association. The reply to my queries from London was as follows:

(*a*) The towel rail was purchased and installed by the family.
(*b*) It was connected to a bayonet-cap lampholder adapter.
(*c*) No attempt had been made to earth the rail.

Mr. J. G. Craven and **Mrs. E. Bradley** also contributed to the discussion at Leeds.

[The author's reply to the above discussion will be found on page 252.]

SOUTH-EAST SCOTLAND SUB-CENTRE, AT EDINBURGH, 29TH OCTOBER, 1952

Mr. D. Baird: Edinburgh is a city with a fine gas supply, and the majority of fires start with an electrical fault on an appliance causing current to travel to earth; often an extra way to earth is provided by the unofficial contact of compo gas piping with the electrical installation. At the point of contact the gas piping is punctured and the gas ignited, sometimes with disastrous results. This hazard will be reduced in future as the Gas Board are now using 19 gauge copper tubing for new and additional installations.

I endorse Mr. Swann's claim that steel conduit with outlet boxes at all points provides a very safe job. The only trouble I have come across on these installations have been earth faults on sunk switches suspended between the plate ring and the fixing screws in the box; the remedy is a grid in the switch box or careful fixing for the depth of the plaster. Broken bushes on plug outlets cause earths on the plug plates and give rise to trouble.

Thermal relays appear to me to be an excellent means of protecting expensive television sets, although some makers have designed fuses with a cold surge characteristic permitting the surge at switching on, but when the fuse has warmed up it will blow on a small percentage overload to its normal rating.

In conclusion, I strongly recommend periodic inspection of all unattended automatic appliances such as immersion heaters, refrigerators, air compressors, fan space heaters, etc. Nowadays so many appliances have considerable wear that the old policy of fit and forget no longer applies.

Mr. J. L. Wood: In connection with the prompt clearance of earth faults, the author refers to the high reliability of transmission protective gear. Given the same high degree of skilled maintenance, no doubt automatic devices on consumers' premises might approach a correspondingly high reliability, but the degree of maintenance of the average consumer's installation must be very low indeed, and if the protective devices are maintained by the consumer they are unlikely to get much attention at all. It seems to me that this is where the automatic device will fail, although in itself it may be an excellent piece of apparatus. Even regular checking of its mechanism is difficult to do effectively in practice. The idea to get meter readers, for example, to push test buttons seems attractive enough, but, as the author says, it tends to imply responsibility and anything which does that is avoided like the plague.

The Swiss may put the responsibility on the supply undertaking, but I fancy that their wiring specifications are more tightly framed than ours and have statutory powers behind them.

[The author's reply to the above discussion will be found on page 252.]

MERSEY AND NORTH WALES CENTRE, AT LIVERPOOL, 3ND NOVEMBER, 1952

Mr. A. V. Milton: The author refers to an overload test on cables in conduit, the insulation being reduced to ash but still operating. I recently came across a case of v.r. cables in conduit working on medium voltage; they had been subjected to heat 10 years previously when the premises had been on fire and apparently after the fire the wires had been tested satisfactorily and had been put back into service, but they had broken down 10 years later and when the cables were drawn out of the conduit there was no insulation at all on a considerable length of the conductors. Obviously there had been ash there, and that had fallen away when the cables were disturbed, but the interesting point is that though this installation was in an engineering shop subject to machinery vibration the cables had functioned satisfactorily in that condition for 10 years.

The author asks for information on instances of conductor breakage caused by corrosion. I do not know whether he wanted that for domestic premises only, but I can cite the case in a tannery where t.r.s. cables were run open on cleats and a considerable amount of trouble had resulted from conductors corroding through because of the rubber sheathing and insulation cracking where it was deformed by pressure under the porcelain cleat, and through the cracks the corrosive atmosphere was able to attack the conductor.

The "Loop Testing" section is very interesting, although in Fig. 1 I am very sorry to see that the illustration of the socket shows the earth line neutral terminals in wrong positions; in a clockwise rotation they are shown as earth-neutral-line which is a contravention of The Institution's Regulations.

Tables 3 and 4 are particularly interesting, and I wonder whether they point to the unsatisfactory results of earthing to water pipes. Table 3 shows 13 tests, 11 of which are water-pipe earthing and only 2 of these were satisfactory, one of these being very doubtful. Table 4 shows better average results and the analysis of these is interesting. The method of earthing in 4 instances is cable sheathing and out of these 3 show satisfactory results. There are 9 tests with water-pipe earthing and 3 of these are satisfactory; of the 9 tests with electrode earthing only 2 are satisfactory; 8 tests have uncertain earthing and 4 are satisfactory, the uncertain methods of earthing apparently being better than the water pipe and electrode earthing.

I think it is fundamentally wrong that such an important function as the earth-return path should depend on a water system in which electrical continuity does not form part of its design or purpose, and the operatives who work on it are usually not *au fait* with the needs of electrical continuity, nor can they be expected to be; they are concerned with supplying water. I think in this matter the electricity supply industry should stand on its own feet and provide a complete electric supply system including earth-return path. It is not sufficient to provide live and neutral conductors and then in effect tell the consumer that the

earth can be picked up at the substation. There is no doubt that supply authorities are becoming aware of their responsibilities and are permitting the use of supply cable sheaths for earth return, but usually only when other forms of earthing are not available, and usually asking for an indemnity. In this area the supply authority proposes on new services to provide a terminal block to which the consumer will connect his earthing system, and wherever practical the authority will connect this terminal to the service cable sheath or aerial earth wire. When the consumer's earthing system is satisfactory the authority's earth is additional protection, but when the consumer's earthing system is not satisfactory an indemnity is asked for.

Mr. W. B. Parkinson: Referring to Table 1 I would like to ask the author if the figures given for wire and cable include accessories and control equipment; if so, before we draw any conclusions about the effect of wear and tear, we must eliminate from these figures the fires due to the use of new materials and techniques, of which I am sure there were quite a number during the years quoted.

It seems to me that two possible fire dangers can arise from the use of cartridge fuses, first the fuse gear being designed for the small cartridge links will lack the breaking capacity needed to clear faults when fitted with wire links, and secondly, while quite rigorous tests using brine have failed to produce tracking on some materials, the spraying of hot metal from a wire fuse invariably does so and may result in a most damaging fire. Would it be reasonable to require a general provision in fuse gear for the accommodation of both cartridge and alternative wire fuses? Some manufacturers already do this. The important fact here, I think, is the cost of replacing cartridge fuses.

The author has given most interesting information on thermal protective devices. I wonder if there is a suitable type which could be incorporated in a socket-outlet. I ask this because I think it would be of the utmost value in cases where the cable is insulated with polythene or other plastic medium.

Some of these thermal devices are highly efficient and capable of performing a duty which is high in relation to their current rating. This applies particularly to the current-operated thermal devices. I wonder if the author has given any thought to the possibility of using such devices in the place of fuses for the protection of sub-circuits. These at least have the advantage of preventing over-fusing of such circuits, and incidentally they may be economical in comparison with cartridge fuses.

Mr. H. C. Nicholls: I have tried to break down, as requested in this paper, the causes of fires under the heading "Wires and Cables," and as from the paper I take it that the item "Other Apparatus" includes fuse boards, switchgear, etc., I have broken down fires under these particular headings as follows:

In the last few months, roughly speaking, 69 fires, out of about 150 attended, would be classified as coming under the headings "Wires and Cables" and "Other Apparatus," yet although the wiring and fittings may have been found to be badly damaged, in 33 cases the cause of fire could be attributed to an extraneous cause.

Faulty hearths and defective chimney flues, etc., accounted for 11 of these cases, while 21 were due to "dropped lights" (cigarettes and matches).

An unfortunate number of fires were caused by gas pipes becoming ignited where in contact with an earth wire. Further investigation of these 12 cases is being made to ascertain if the installation fault primarily responsible was in any way associated with the age of the installation.

Two fires were caused by flexible cords becoming ignited after being saturated by rain percolating through defective roofs.

On the other hand, the number of fires caused by short-circuit faults was only 4, in one case ascribed to the fact that cables were drawn very tight over the sharp edges of a brick, and in another case a conduit elbow out of joint had allowed the sharp conduit edge to cut through the cable insulation.

Loose connections accounted for 8 of these fires and one wondered whether fires from this cause are more prevalent in areas where there is heavy traffic and machine vibration than in residential areas. The current trend to install Bakelite fittings in houses is already telling its tale; for 5 fires were caused by Bakelite trouble, tracking, etc. A well-known maker of fuse gear uses a very poor mixture for Bakelite manufacture, and a lot of trouble has been experienced from this particular cause, slight tracking or a loosened connection leading to almost complete combustion of the fuse gear. Another well-known manufacturer sells an excellent switch in all points except for the fact that the main terminals, which are designed to take heavy cables, have insufficient anchoring, and under cable strain, the switch mechanism is forced out of alignment, causing arcing which often results in a breakdown of insulation.

We in Liverpool cannot make periodic inspections of all installations; but we have to inspect installations where there is a change of tenancy or where we propose to change the supply, and these inspections suggest that many old installations are standing up very well, many should be rewired right away and many installations hardly 5 years old are not to be compared with old installations as regards quality and condition.

Mr. H. J. Fraser: It seems to me that at the present time as regards new installations the first effective tests are made by the supply authority; they ensure there is reasonable insulation resistance and the polarities of the various switches and plug points are correct. At that stage the wiring is generally covered up and a good deal of shoddy work can remain undetected. The floorboards are down, plaster is on the walls and wiring is sometimes secured by nails. In one fault I came across some years ago the earth wire was actually in contact in places with the gas pipe. Of course the inevitable happened, a fault on the plug point, and a hole was blown in the gas pipe. Fortunately the resultant gas leakage was detected in time before any serious results occurred. I do not know whether the author will advocate, particularly in connection with local authority housing schemes, that there should be some inspection while the work is going on?

The other point I had in mind was that this is one of the countries where anybody can operate as an electrician or indeed describe himself as an electrical engineer. In some of the Commonwealth countries there is a system of registration and the electrician must have some certificate of competency. Does not the author think it is high time we had a system of that sort to obviate shoddy and possibly dangerous electrical installations?

Mr. J. Eccles: If the author had excluded 1946 from Table 1, the trend would have been downwards instead of upwards. The other years are all slightly above 16%—1950 is rather better than the others.

I agree with Mr. Swann that it is impracticable to inspect all the old installations, and what we have to do is to protect the old and the new installations from the consequences of their own defects.

With regard to circuit-breakers and thermal devices, may I enter a plea for large contacts for these devices? We all know that if contacts are big enough and have enough body of metal they have large thermal capacity in themselves and will interrupt an alternating current with a micro-gap. Some of these devices fail because the contacts are inadequate, and if the author is interesting manufacturers I should like to suggest that reliability would be enormously increased if they paid attention to this particular detail.

The National Inspection Council is only intended to improve the quality of new installations and to do it by sample testing, because to do otherwise would mean an enormous inspectorate duplicating the work of the supply authorities. By a process of registration of contractors who generally and continuously comply with certain standards, we hope to raise the quality of electrical installation work.

On the question of testing new apparatus, I believe every Area Board has a testing house at which it will gladly test new devices and comment on them to the manufacturers.

Mr. H. Norris: I was interested in Table 2, and I still think it is a pity we cannot get some more details as to the causes as there may not be so much in it at the finish. It would be possible, of course, to obtain accurate information from the insurance companies as to every single fire, but it would be a colossal task because a good many are fairly trivial.

The author asks for the opinion of engineers who have in some way been concerned with the upkeep of the older installations in use, etc., and whether age increases the electrical fire risk. May I suggest from my own experience that age does not necessarily create fire risk.

I cannot bring forward anything particularly useful as an alternative to inspection except the suggested protective devices. As regards the ordinary domestic consumer, he, of course, wants protecting against himself because what is easier than to go into a shop, buy any number of appliances and plenty of wire and if something goes wrong the fuse will blow. If in the event of fatality there was some serious penalty in the case of such a consumer there might be a different story.

The author expresses some doubt whether many consumers would crawl regularly into the cupboard under the stairs to press the test button of a combined unit or any other form of circuit-breaker. That brings me to another point, namely that the repositioning of the ordinary domestic consumer's service should be considered. It is an obvious need; also the finish at meter positions in many hundreds of cases is far from good.

As regards appliances, I would inquire whether in the author's opinion there is any merit in having a testing house certificate attached to each appliance before sale—similar, say, to the American practice where the Underwriters' Laboratories label or grade various appliances.

[The author's reply to the above discussion will be found on page 252.]

WESTERN CENTRE, AT BRISTOL, 8TH DECEMBER, 1952

Mr. G. L. Leighton: The author has referred in particular to the electrical risks in domestic premises, but I would like to suggest that the smaller type of factory bears many resemblances to a domestic establishment in its electrical arrangements. There is, however, one important difference in that there is statutory right of entry for inspection into premises subject to the Factories Act, whereas no such right exists for domestic premises, and inspection is therefore often a difficult matter. I have myself had considerable experience of inspecting these small factories, and I would like to support the point made by the author in Section 3 of the paper regarding the extreme difficulty of making a thorough inspection of the electrical installation in most types of building. A complete inspection and test could in fact hardly be carried out without considerable dismantling of the building, and more expenditure of time than is usually feasible.

In connection with small factories in country districts, I have been particularly interested in the author's remarks on sensitive earth-leakage circuit-breakers, and have tested many such installations by the acid test of applying a fault to the system. There have been many occasions on which the sensitive earth-leakage breaker was non-operative, and the reasons for this can I think be stated under three headings:

(1) Failure of the earth-leakage breaker itself, due to lack of maintenance.

(2) Accidental disconnection or breakage of the earth connection for the voltage coil.

(3) Accidental short-circuiting of the voltage coil by fortuitous earth connections.

Presumably all these earth-leakage circuit-breakers were installed on these small premises either on the instruction or recommendation of the electricity supply company or authority, possibly many years ago, and before the present authorities were set up. It would therefore be interesting to consider who should be held responsible for the maintenance in good condition of these devices, on which the safety of the consumer so greatly depends, and the purpose of which he so little understands.

Mr. D. G. Ashford: Care should be taken to avoid the risk of fire when connecting immersion heaters, especially those fitted in airing cupboards.

A faulty connection between resistance wire and an internal terminal can be the cause of overheating. Heat developed due to arcing is likely to travel along the external conductor and this may be sufficient to ignite rubber-covered conductors.

Mr. R. G. Sell: The author has dealt with wiring and appliances, but does not refer to fittings such as lampholders and socket-outlets. Dimensions must necessarily be small, but I think makers should pay more attention to securing maximum clearances and to use of materials suitable to resist tracking under conditions where moderate degrees of condensation and/or dust deposition are likely to occur. This was recently brought home to me forcibly in my own domestic installation when a tracking failure to earth on a British Standard 13 amp socket destroyed the fitting and as the ring-main circuit fuse failed to give protection the arc had to be blown out. The condensation was only relatively slight and fortunately someone was there so that no serious damage occurred apart from that to the fitting.

Mr. R. P. Hooper: I should certainly like to endorse Mr. Swann's remarks regarding earth-leakage circuit-breakers in that they are liable to break down under working conditions, and over a fairly wide rural area I have found that either they refuse to operate when called upon to do so by fault conditions or they operate much too easily when, say, moisture percolates into a cooker hotplate through the boiling over of a saucepan, etc.

This generally happens when the premises are situated some distance from the service centre.

Mr. G. O. McLean: As pointed out in my planning paper, this country doubles its electrical sales every $7\frac{1}{2}$ years or, to use recent figures for the South West area, we have increased our sales by 53% in the first four years of nationalization. We are connecting at least 25 000 new consumers every year. Some allowances must be made for an increase in the number of accidents because of these phenomenal increases.

I must stress also the fact that Mr. Swann is preaching to the converted, and I would like to ask him whether he has any suggestions for getting his message over to the ordinary domestic consumer.

Mr. Swann has asked us to comment on the form of electric blanket loading, and in reply I would unhesitatingly vote for the adequately loaded blanket with a separate bimetallic strip incorporated in a bedside control similar to the control in the thermal demand indicators which resets after a predetermined period.

[The author's reply to the above discussion will be found on page 252.]

TEES-SIDE SUB-CENTRE, AT MIDDLESBROUGH, 7TH JANUARY, 1953

Sir Edward Anderson: The "ordinary consumer" in this district apparently thinks that if a fuse fails, he should replace it with a much bigger fuse. The "ordinary consumer" referred to by Mr. Swann is in a more advanced class. The whole question is, to my mind, one of a system of periodic test and inspection, and as far as Electricity Board inspection is concerned, I hope that there will, in the near future, be a national standard of inspection. At the moment it varies a good deal in different areas.

In Table 1, I was very concerned to find that the percentage of fires "caused by electricity" in this country between the years 1946 and 1950 varied between 14·5% and 16·8%. When I think of the large number of cigarette smokers, people carrying blazing coals from room to room, people drying clothes in front of open fires, then I am astonished. I was also astonished that such a large percentage, approximately between 31% and 40%, are described as being caused by "wire and cable."

I felt it would be of interest to quote some local figures, and thanks to the courtesy of the respective Local Fire Chiefs for Stockton, Middlesbrough and West Hartlepool, I can give some figures. It is interesting to compare our local figures with the overall national position. For the years 1948 to 1952 inclusive, the total number of fires in Middlesbrough (excluding chimney fires) was 1 086. Of these, 91 are assessed as being caused through electrical defects. This represents approximately 8·5%, which is little more than half the national average.

The figures for West Hartlepool, for the same years, are, total fires (excluding chimney fires) 624; total "electrical fires" 52, or again about 8½%.

In the case of Stockton, the figures for the same 5 years are, total number of fires (excluding chimney fires) 392; total number of electrical fires 51, or about 13%.

It seems to me surprising that Middlesbrough and West Hartlepool should be so much lower than the national average, and obviously one wonders why. Stockton is only a little less than the national average.

One is bound to reflect that if the national average is 16% and some towns are only 8%, then other towns must be well above 16%. There is obviously great need for action in such places.

I have not given the detailed "electrical analysis" of fires caused because the method of setting them out by the different authorities has varied somewhat.

I think that in Middlesbrough there are probably two main reasons for our good electrical record:

(1) In about 1939, the Corporation started, and from 1948 onwards the Board have continued, a system of inspections in all properties which change hands. Many of these are the older type of properties, and I think a great deal of good has resulted from those inspections. Following the inspection, the consumer's attention has been called to those points in his installation which constitute a risk of fire and a risk to life.

(2) The second point is that in Middlesbrough one can secure an easy and effective earth throughout the town by fixing on to cold water pipes. Like the author, I think that many electric fires arise from earth-leakage current, and that in those places where good earths are easily obtained the fire risk is diminished.

I would criticize Table 2 as offering very little real information. The operative word is "defective," and it all depends, as Joad would have said, on what you mean by "defective." The percentage of "defective" appears very high, but some of the faults may be very small.

I am convinced that the fire risk of an electrical installation does increase with age, owing to the brittle insulation, and I think that the problem is largely that the life of a building, even a poor building, is 100 years, and the life of rubber insulation is about 30 years, or in some cases, less.

The author raises an interesting point as to the difficulty of taking earth-leakage current tests. My own view is that they are scarcely ever taken, and it may well be that in commercial work they are never taken. Megger tests on the insulation resistance are always taken; the trouble is, of course, that in completely dry buildings they may be very misleading.

I was surprised that the author's tests proved that it was very difficult to set fire to certain cables under overload, but this no doubt accounts for the fact that relatively few buildings do burn down. Many certainly stand which should, on the technical evidence available, burn down.

[The author's reply to the above discussion will be found on page 252.]

SHEFFIELD SUB-CENTRE, AT SHEFFIELD, 21ST JANUARY, 1953

Mr. R. E. S. Fisher: Like many others I was very surprised at the high percentage of fires caused by electric refrigerators. As you know electric refrigerators are of two types, thermal, i.e. operated by a heating element, and motor-driven compressor.

From what has been said about the cause of these fires it would appear to me that the thermal type may possibly be the safer. Can the author say if this is borne out in practice?

Mr. E. J. Lilleker: At the beginning of his paper, the author emphasized that he was dealing with fire risks of an electrical installation as distinct from the shock risks. In view of my electrical contracting experience which has pointed to more accidents to personnel due to shock than to fire, I wish Mr. Swann had dealt with the shock risk as well as the fire risk. However, Mr. Swann perhaps can give us comparable figures for accidents due to shock and fire.

Mr. W. Allsop: Whilst agreeing with the desirability of maintaining a high standard in domestic electrical installation work, do we, as electrical engineers, rate the fire risk too highly, since the insurance companies are prepared to insure premises, no matter how good or bad the electrical installation may be, against fire from any cause, at the very modest premium of £1 per annum per £1 000 insured?

In view of these seemingly very low premiums, will the general public ever be persuaded to incur much greater expenditure on remedying installations below standard without the use of compulsion?

Mr. J. L. Ferns: I propose to limit my remarks to two aspects of the paper. In the first place I am wondering where the author expects the labour to come from for his ambitious testing proposals. In the District I manage there are over 50 000 consumers. Assuming that an installation inspector could do 10 installations per day and that installations were checked once per year, it is clear that I should require twenty men. As these men would require to have certain qualities in addition to the skill of an electrician it seems fairly clear that they would not be forthcoming under our present industrial set-up. Consequently, I see no hope of carrying out the author's ideas even though they are most excellent so far as they go.

In the second place I wonder if the author has explored the use of s.e.w. (separate earth-wire) sufficiently far. As earth-leakage trips and protective multiple earthing have so many practical disadvantages it appears to me that we ought to make our electrical distribution systems self-sufficient. The days have gone by when we could rely on water mains or substation earth

electrodes. It must not be thought, however, that the use of s.e.w. will make distribution costs much higher than they are at present if one bears in mind the heavy cost of trying to create a satisfactory substation earth electrode—a point which the author's tables amply emphasize. I have developed formulae to cover the three systems, and when practical costs are applied to these formulae the results show a gain for s.e.w. in some cases to offset those cases where s.e.w. is higher in cost. I believe, however, with the author, that cost is not the most important of the criteria concerned and that s.e.w. should be adopted even if it does show a small financial disadvantage.

Mr. A. Haddock: The problem of ensuring that the domestic consumers' protective arrangements will operate when necessary becomes in practice a problem of ensuring a sufficiently low-resistance path to the transformer neutral point. The commonest way of attempting this is to try to obtain a low resistance to earth on the transformer neutral point and at the consumer's installation. We are all familiar with the difficulties of ensuring this in some cases. The important fact, in my view, is that although familiar with these difficulties, the electricity supply industry has done virtually nothing in the past 25 years to improve the situation. I suggest that the author should use his great experience in this matter to persuade the appropriate authority to issue a code of practice covering the provision of protective arrangements. My own preference is for fuses wherever practicable. They have been enormously improved by modern developments, so that they are now an efficient and safe protective device. They fail to safety and require the minimum of maintenance.

My own views are: (1) In the case of underground distribution networks, where the lead-sheathed underground cables can provide a continuous metal path from consumer's installation to transformer star point, the supply authority should accept responsibility of providing, at the service position, a suitable connecting lug to which the consumer's earthed metal should be bonded.

(2) In the case of overhead distribution networks, a continuous metal path in the form of an aerial earth wire should be provided as part of the distribution network. I feel confident that this is economically practicable for a great percentage of overhead distribution networks, and the code of practice should indicate the density in consumers per route mile down to which this method is considered the best. Again the supply authority should provide a connecting lug to which the consumer's earthed metal should be bonded.

(3) In those cases where development is so sparse that an aerial earth wire is not economically the best, the supply authority should provide some form of earth-leakage circuit-breaker, possibly with the differential feature advocated by the author. Since the supply authority provides the circuit-breaker, the supply authority would be responsible for maintenance and the consumer would have to be content with one circuit-breaker to control the whole installation. I do not think there is any serious objection to this. There may be room for some form of multiple protective earthing of the neutral intermediate between cases 2 and 3, but I am not personally very fond of multiple earthing on a very sparsely developed network.

[The author's reply to the above discussion will be found overleaf.]

NORTH STAFFORDSHIRE SUB-CENTRE, AT STOKE-ON-TRENT, 18TH JANUARY, 1954

Mr. C. C. Pimble: I feel that fire risk from old installations is likely to increase with age, owing to deterioration not only of the components but of the buildings themselves. I suggest the risk might be reduced if fire insurance companies required a certificate certifying that an installation is in good condition, as a condition of renewal of the premium. Contractors' organizations and Area Boards could also offer an inspection service at a nominal fee.

The danger of leakage current arising from unsatisfactory earthing is a very real difficulty. In this area the Supply Board will provide earthing terminals on their service cables where appropriate, as an alternative to the doubtful water pipe. For new rural systems I think multiple earthing is the best solution. On existing rural systems I have experimented with an air-break circuit-breaker at the substation operated by an earth-leakage trip, but the experiment was not carried to a successful conclusion.

The device illustrated in Fig. 5 seems to offer a good solution, although separate earth electrodes to obtain the voltage feature have the disadvantage that they are liable to interference and require frequent inspection. In the event of a device similar to Fig. 5 being produced at a reasonably low price I think the supply undertaking might bear the first cost.

Mr. L. Goodall: Table 1 shows that about 40% of the fires are caused by wire and cable and only a small number by flexibles. This is surprising. Does the figure include fires due to defective conduit or lead sheath continuity which might cause arcing when carrying fault current?

Table 3 shows about 85% and Table 4 about 60% defective earth loop resistances. Are these average or selected results? In a large number of local tests taken where the consumer's installation is earthed to the water pipe, 10% were above 4 ohms where the substation earths were interconnected by an extensive cable sheath network, while 29% were above 4 ohms where the substations were mainly independently earthed.

The fusing factor of 1·8 or 2·0 used appears to be optimistic; h.r.c. fuses generally require two or three times rated current to blow in one minute and three or four times to blow in less than 10sec. To blow in less than one minute the loop resistance must not exceed 3 ohms for a 30amp fuse or 1·5 ohms for a 30amp fuse. After allowing one ohm for the earth-continuity conductor, there is not much margin for two electrodes in series when a 30amp fuse is used. It is desirable to reduce the main circuit to a minimum and rely on branch fuses to clear.

In an area liable to subsidence, cable joints are frequently drawn apart and the neutral conductor usually parts first. If a consumer beyond the drawn joint has a neutral earth fault on his installation, the out-of-balance current on the main beyond the fault will find its way back to the supply transformer via the consumer's earth fault. Owing to the adoption of single-pole fusing, this current would not be interrupted and the risk of fire would be considerable. The double-pole circuit-breaker shown in Fig. 5 would deal with this satisfactorily.

In response to the invitation in Section 10 to comment on the question of total interruption of supply on the occurrence of a fault, it is considered that the circuit-breaker should not control the lighting as well as other circuits. The light should not fail just when the housewife has had, say, a short-circuited iron flex. So far as possible an all-insulated circuit should be used for the lighting and 5amp fuses which would blow in one minute with a loop resistance as high as 16 ohms.

Mr. S. Scholefield also contributed to the discussion at Stoke-on-Trent.

[The author's reply to the above discussion will be found overleaf.]

THE AUTHOR'S REPLY TO THE ABOVE DISCUSSIONS

Mr. H. W. Swann (*in reply*): Knowing that many of the suggestions made in the paper are highly controversial I have been surprised at the large measure of support for the views expressed. In general, almost everybody agrees that something should be done by somebody else, and it is for that reason I have stressed the inclusive responsibility of the electrical industry as a whole to its non-technical customers.

Several speakers regretted that I did not refer at any length to electric-shock causation, but the paper was expressly written to indicate the growing risk of fire as distinct from shock.

There was widespread agreement as to the impracticability of starting any general scheme of inspecting consumers' installations, but few speakers faced the age question squarely in the sense that no insulation has everlasting life. My point, which was not widely appreciated at the meetings is that, recognizing the difficulties of worth-while inspection of installations, attention should be focused on providing automatic protection which will work, and on looking after it, so that when the inevitable troubles eventually occur they blow a fuse, open a circuit-breaker, or operate a thermal relay, instead of burning the house down.

Almost every speaker who mentioned it agreed that uncleared earth leakage would be likely to cause fire, but there was no general realization of the extent to which immunity is achieved by the long protecting arm of coincidence. There must first be a fault in the insulation of the wiring, or in that of an appliance, which is restricted by resistance, internal or external to the premises, to a value less than that at which the current protective device will operate. If internal, this resistance must be concentrated, and the I^2R loss at that point must be sufficient to cause a hot spot reaching a temperature high enough to set something on fire. There must next be something to catch fire, and if there is not, the hot spot merely contributes towards the general amenities of the house in cold weather, in the same way that hot plugs and sockets assist an electric radiator. If fire is started, it must be capable of spreading (as distinct from dying out) and this again must occur at a time when there is nobody about who can see, smell, or hear. When all these conditions are simultaneously satisfied a call is eventually received by the fire brigade and the occurrence takes its place as one of the 7 000-odd fires per annum classified in Table 1 of the paper. Since I wrote the paper the figure has gone up to 8 000, and it is a fair inference that the initiating factor of uncleared earth leakage must occur by itself on a large scale without doing more than add to the revenues of the Area Boards, who might take this point into account when considering what "service" they can afford to their consumers.

Two or three speakers made an entirely justifiable point about the number of fires attributed to electricity in Table 1. In relation to the 13 million or so installations in the country they pointed out that the total number of fires recorded is only 0·06%, which sounds very different from the way I expressed it—as 18% of the total fires from all causes. It was added that the *relative* risks should be reviewed dispassionately, and this was certainly the idea I had in mind when I chose the Fire Brigade statistics, which compare all the different kinds of risk, as the best means of presenting a realistic picture of the position. I agree too that advice given to consumers should not be offered in a way which alarms them, and I would point out that the paper was written for technical engineers and not the public at large. In the 32 years during which I have occasionally offered advice to factory occupiers on electrical matters, I do not believe I have ever caused them alarm, but I cannot say that the converse is also true.

Members at most of the discussions referred to the measures taken in their part of the country to reduce the earth-fault-path resistance, such as by earthing to cable sheath, providing direct aerial earth-wires, adopting relaxed protective multiple earthing or reinforcing earth electrodes at supply stations or transformers. Little was said about the cost of these steps, although my paper gave a lead in that direction in Table 5, either initially or as regards the subsequent inspection and testing necessary to ensure that the conditions are maintained. The point is of some importance because this kind of expense is incurred in the interests of the consumer, but nobody suggested that the latter should pay for it, although it was thought that the cost of installing and maintaining a circuit-breaker as an alternative measure should be carried by the consumer. This is hardly a consistent attitude but it is certainly customary, and the paper suggested a revision of outlook which would take a more comprehensive view of the problem. Efforts to reduce the fault-path resistance are really directed towards providing conditions under which the supply authority hopes that consumers' automatic protection will work, and there may be many cases where less money might be spent on improving the protective devices instead. The two alternatives are fundamentally related, and real "service" should tackle both with that knowledge of the conditions which is best obtained by making loop tests in the way advocated in the paper.

There was considerable interest in loop-resistance measurement, and I regret that the exhibition and demonstration of the loop meter, with other instruments and equipment shown at the London meeting, could not be arranged at the Local Centres. This measurement is essential for ascertaining whether consumer automatic protection will function on earth leakage, and since the paper was written instrument design has been improved and many are being used by supply undertakings, contractors and local authorities responsible for public buildings, schools, etc. Replying to members who inquired about the conditions under which loop measurement should be made, I would say that it should be when a consumer is first connected and subsequently under some scheme of "service" from an Area Board or "contractual maintenance" arranged with an electrical contractor. These are new conceptions, but they are basic to automatic protection of any kind and therefore to measures designed either towards low resistance earth-fault paths or to the type and setting of automatic protective devices. I suppose that the use of a Megger insulation tester was once a new idea, but it has become firmly established as a present-day necessity, and it seems reasonable to think that an instrument which can be used to decide whether the consumer's automatic protection is likely to work will presently be regarded in the same way.

With respect to loop testing, several speakers gave their views on The Institution's Wiring Regulations Nos. 1003 and 1005, which deal only with the resistance of that part of the loop which is on consumers' premises. Some members thought the Regulations should be amended to make loop resistance the criterion, which is my own view, whilst others held the opinion that the one-ohm rule for consumers' continuity resistance was satisfactory in conjunction with good earthing. Against this, however, were many stories of cases where the earthing was anything but "good"—amounting often to something which was obviously very "bad." These undefined terms, however, do little more than reinforce the case for measurement, which is surely a policy likely to commend itself to an engineer.

Many of the views expressed were diametrically opposed. For instance it was said that it is difficult to sell safety—a remark which brought the rejoinder that it should be provided free. Here again, however, the terms are undefined, and it must be remembered that the non-technical consumer is not in a position

to judge how much safety he should purchase or how much should be given free, or by whom, or when. He relies—because he must—on the integrity of the industry, and as a customer he is entitled to expect good advice and good service. I take the view that it is a mistake to think that reasoned and well-balanced references to electrical safety are detrimental to sales policy—indeed the underlying theme of The Institution's Wiring Regulations is devoted to that subject.

The strongest opinions were advanced about consumers who extend or modify their own installations, replace and stiffen their own fuses, bring home and connect up new appliances and in many other ways incur risks of which they are presumably unaware. The numerous speakers on this subject did not seem to think there was any way of preventing this widespread practice, and when it is remembered that many installations have in fact been carried out, extended and altered from time to time by almost non-technical tradesmen practising as "contractors," this feature of the discussions did indeed present a picture which perhaps afforded some justification for a paper entitled "Some Safety Aspects." Few of the non- or semi-technical people referred to have any notion beyond contriving something which will work, and their criterion of fuse setting is something which will not blow on the maximum load. Thousands of installations have been extended piecemeal by handymen possessing no knowledge of the original carrying capacity of the wiring, and thus much insulation must have been baked, and become brittle material susceptible to damp and disturbance.

In the course of the discussions references were made to the possibility of fire being caused by insulation faults in the neutral conductor which is normally not under voltage stress. Such faults would be dormant, possibly for long periods, but if there is appreciable resistance at supply-transformer neutral-earth connections an uncleared phase fault may cause a potential difference across this resistance and thus voltage rise in the neutral. Under such conditions the dormant neutral fault would become active and carry some part of the load current to earth, possibly with risk of fire. The position would become more serious if there were a neutral fuse which might blow and thus cause all the load current to return through the fault to earth instead of by the conductor. There is experience of this trouble in districts serving the older classes of property where dormant faults may be common and go undetected. The current-balance-type circuit-breaker described in the paper would afford protection in the event of leakage to earth from the neutral conductor.

A number of members supported my view that since no system of inspection of existing electrical installations is practicable, except perhaps at change of tenancy, any action taken can be only on the much smaller scale of trying to provide and maintain consumer automatic-protection capable of operation before the places go on fire. In the paper I have described various forms of fuse, voltage- and current-balance types of circuit-breaker, and thermal relays which are available for consumer protection, but speakers all recognized the necessity of servicing such devices, and one of them suggested they should be treated like main service fuses and sealed so that consumers could not render them inoperative.

Taking a long-term view I think many of the points made in the paper and by speakers in the various discussions will assume more importance as time goes on, if only by the force of events. There was general awareness of unsatisfactory conditions, and I have tried to offer some constructive suggestions for their relief which may in the future become justified.

DISCUSSION ON "INSULATION OF ROTATING ELECTRICAL MACHINERY"*

SOUTH-EAST SCOTLAND SUB-CENTRE, AT EDINBURGH, 20TH OCTOBER, 1953

Mr. V. P. Mackay: I was somewhat surprised to note the relatively high value of water absorption in glass impregnated with silicone, particularly since I understand that silicone is a water repellent. Is the water absorption due to each glass fibre being hollow or to silicone being hygroscopic?

The author mentioned that the aircraft industry demands machines insulated to withstand operating temperatures of 200°C. The aircraft industry is not alone in this, since coal-cutter motors and the like, although ordered and designed for continuous rating (which is really a six-hour rating for this class of motor), are often being used on continuous mining, i.e. operating 24 hours a day for five or six days per week, and at winding temperatures of between 150 and 200°C. For how long will the windings operate under such temperature conditions plus the hazards of condensation and leakage of oil into the stator frame from the coal-cutter reduction gear box?

Mr. E. Jones (*in reply*): The values of water absorption for silicone-glass laminates quoted in Table 2 of the paper were typical of the laminates available up to the end of 1952. In my contribution to the discussion on the paper by Hawthorn and Messent† I quoted results obtained on more modern glass laminates, from which it will be noted that the performance of the silicone-glass laminates under conditions of high humidity is extremely good. I doubt whether the presence of hollow glass filaments is important; the most important features in the production of a high-quality silicone-glass laminate are probably the method of pre-treating the glass and the laminating technique.

Regarding the life of coal-cutter motors under the conditions stated by Mr. Mackay, it is almost impossible to make an estimate. It is assumed that the motors have class-B insulation. To operate such motors at a winding temperature of 200° C for long periods is bound to reduce their useful life very considerably. If the manufacturer knows that the motors have to withstand such temperatures, the insulation materials and the insulation design can be such as to give considerably more life than would be the case with normal class-B insulation. Special insulation would, of course, increase the cost of the motors appreciably.

* JONES, E.: Paper No. 1487 M, March, 1953 (see 100, Part IIA, p. 208).

† HAWTHORN, A. N., and MESSENT, S. W.: "The Properties of some of the Newer Laminated Plastic Insulating Materials," *Proceedings I.E.E.*, Paper No. 1495 M, March, 1953 (100, Part IIA, p. 190).

DISCUSSION ON
"THE CO-ORDINATION OF INSULATION OF HIGH-VOLTAGE ELECTRICAL INSTALLATIONS"*

SOUTH MIDLAND CENTRE, AT BIRMINGHAM, 2ND NOVEMBER, 1953

Mr. E. V. Hardaker: My remarks refer to the application to the 132kV Grid system. Over the last 13 years in the Midlands Division Area there has been a total of 53 outages believed to be caused by lightning, 50 of these being line flashovers and three being transformer flashovers. Except in one case where a transformer winding was damaged, the damage was insignificant, and there were only two short interruptions of supply. Bearing in mind this experience, together with the low isoceraunic level in this country and the fact that it is standard practice to install standby transformer capacity at supply points, there does not appear to be any economic justification for the fitting of surge diverters on Grid transformers of the bulk-supply and inter-bus types. With a generator transformer, however, particularly if it is part of a unit-type generator, there would appear to be some justification for a surge diverter. A fault on such a transformer might cause prolonged outage of the complete unit resulting in increased generating costs—with a modern 60MW set this might amount to as much as £5 000 per week.

Is the author satisfied that the surge diverter will afford complete protection from a direct lightning stroke? A case has been experienced where the transformer winding was damaged even though the 26in rod-gap had flashed over. Admittedly the rod-gap would be slower in operation than the surge diverter, but the excessive damage that usually results from a direct stroke leads one to wonder whether any form of protection would save the transformer from damage in such circumstances.

Reference is made in the paper to the testing of bushing insulators for power factor, and a test voltage of 88kV is mentioned as being necessary for 132kV bushings. I suggest that this figure may be unnecessarily high, and that a lower figure of 30–40kV may be adequate, and incidentally more suitable, for site testing. This suggestion is based upon the results obtained from recent site tests made on 132kV bushings, where the test voltage was about 30kV.

Mr. H. F. Jones: The co-ordination of insulation is necessary on three counts:

(*a*) Economy of materials.
(*b*) Protection against over-voltages.
(*c*) Continuity of supply.

It is now possible to design a line for a statistically predicted lightning performance. In a large number of strokes to an overhead-line system back flashover results, which is largely the result of high tower-footing resistance. I believe that (*c*) can only be satisfactorily met by more attention to lowering the average footing resistance.

A great deal of research has been undertaken in America on the actual probability of lightning striking a system, but only recently have such investigations begun in this country. Until much more information is available it will not be possible to take full advantage of the economies permitted by insulation co-ordination.

There is also considerable scope for further research into the behaviour of composite insulation when subjected to short-fronted waves, which may well permit further economies in taking fuller benefit of the upturned portion of the characteristics clearly seen in Fig. 1 of the paper.

The use of surge diverters has, up to the present, been largely associated with the transformer. For the higher system voltages, however, the circuit-breaker is frequently the more important single unit of equipment to ensure continuity of supply, and for that reason it warrants greater consideration for over-voltage protection.

Mr. A. R. Parish: In Section 2.1.2 the various methods of neutral earthing which affect insulation co-ordination are discussed, but an "effectively earthed system" is defined in two ways which are not strictly compatible. The important point is, of course, that on an effectively earthed system the voltage to earth of a healthy phase must not exceed 80% of the phase-phase voltage during an earth fault on another phase. That is the basic definition, and the one involving sequence components is a very rough approximation. Fig. D shows how approximate it

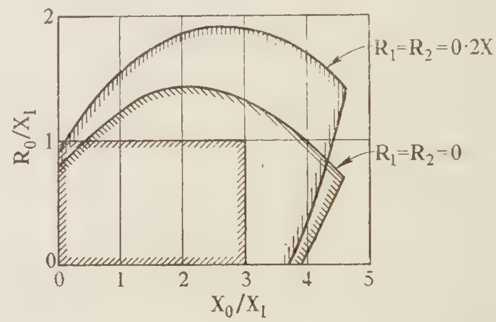


Fig. D.—Limits of ratios X_0/X_1 and R_0/X_1 for maximum line-earth fault voltage not greater than 80% of the line-line voltage.

is, and if, in a particular case, it is considered desirable to calculate X_0, X_1 and R_0, the calculation should be completed by computing the phase-earth voltages rather than by relying on approximate limitations of impedance ratios.

A case has been recorded of a 138kV transmission line without overhead earth wire suffering 133 outages per 100 miles per year. After fitting an earth wire with 46° shielding angle this figure was reduced to 2·2 outages per 100 miles per year. Surely this is better than the "some improvement" mentioned in Section 2.2.2 as the probable benefit of an earth wire.

Can the author give an explanation of the limit of 8 hours a day mentioned in Section 3.1 for the operation of standard bushings on an arc-suppression-coil earthed system under fault conditions?

In Section 3.3.2 the author mentions the use of transformers of 825kV level on a 245kV system. On this system circuit-breaker levels have also been reduced to 825kV, and serious consideration is being given to a reduction to 750kV. Bearing in mind that this system is in a part of the world with an isoceraunic level comparable with that in this country and that, in general, rod-gaps and not diverters are used for protection,

* Cliff, J. S.: Paper No. 1485 S, March, 1953 (see 101, Part I, p. 39).

does the author feel that insulation levels, and consequently costs, might be substantially reduced in this country?

Dr. J. B. Higham: It is true that the a.c., d.c. and impulse strength of air decreases with reduced density, and therefore the effect should be taken into account at high altitudes. However, I disagree with the statement that the breakdown strength of oil is unaffected.

There is evidence* that the a.c., and probably the d.c., strength decreases with decreasing pressure under conditions such as those in a transformer fitted with a breather. The figure of 3·5% per 1 000ft suggested by the author for air would be a suitable allowance to make. The impulse breakdown strength of oil is probably independent of pressure, but it is possible that there is a pressure-dependence for oil-impregnated paper in a transformer. Owing to the heating and cooling cycles, gas will be dissolved and evolved, and bubbles may lodge on or in the paper, where they may initiate breakdown. The gas in the bubbles would have a breakdown strength dependent on pressure, and so, indirectly, might the whole insulation.

Until more is known about these phenomena it is wise to remember that a transformer may have a reduced insulation strength at high altitudes.

[The author's reply to the above discussion will be found on page 262.]

IRISH BRANCH, AT DUBLIN, 19TH NOVEMBER, 1953

Mr. P. G. Boyd: It is stated that, owing to abnormal operating conditions, the normal system voltage may be exceeded for only a few seconds by only 20–30%. I think that is rather a conservative view. In addition to the rise of generator voltage the long-range on-load tap-changing transformers may "run away accidentally to the end tapping."

In Table 2 fuse ratings are listed up to 132kV. Has satisfactory performance been obtained with fuses having ratings above, say, 50kV?

The author mentions the risk of the surge diverters themselves failing, and this is a strong argument in favour of not fitting surge diverters. At least one manufacturer uses protectors for his surge diverters, even though he claims that they are not inferior to those of his competitors.

It was mentioned in the discussion that the best lightning protection is provided in a station by having many overhead lines radiating from the station. When planning a new transmission system this may be a minor factor in favour of using, say, three lines at 100kV instead of one line at 220kV.

There is universal agreement that surge diverters should be located as near as possible to the plant they are intended to protect, but in order to economize in the number of diverters (since they are somewhat unreliable and expensive) one set might be required to protect, say, two widely spaced transformers. What is the longest distance the author would allow?

There are divided opinions on the necessity of using a surge diverter across the neutral bushing of an unearthed transformer. Has the author any views on this matter?

Mr. P. J. Tierney: Our maintenance division has been asked to carry out some experimental tests on the current-breaking capacity of 38kV air-break switches, but the manufacturers are very modest regarding load-breaking capacity, and it is difficult for us to stage such tests owing to the difficulty in getting plant out of commission. We intended to use the 110kV line from Ardnacrusha to Tralee with one 15MVA 110/38kV transformer fed from the 38kV system with the 110kV line switch open in Ardnacrusha. The transformer would be switched on the 38kV side by means of an air-break switch. In effect, the load broken would be the charging current of 95km of 110kV line and the magnetizing current of a 15MVA 110/38kV transformer, amounting to 2·5MVA. However, this would be too great a burden to impose upon any air-break switch, and so we have rejected it in favour of a simple interruption of charging current on 30km of 38kV line, which would amount to 160kVA. Under these circumstances, would the author expect any serious over-voltages? There would appear to be a movement to supplement circuit-breakers by load-breaking air-break switches for voltages as high as 110kV, particularly owing to the cost of circuit-breakers. The on-load air-break switches cost approximately a quarter of the price of circuit-breakers. Do the authors anticipate any difficulty with over-voltages when these on-load air-break switches are used?

We have had difficulty in switching 38kV shunt reactors at Inchicore on full oil switches. The portion of the condenser bushing immersed in the oil was badly tracked after several switchings, and it was necessary to install surge diverters between the switch and the reactor. Since then we have replaced the full oil switch with an air-blast switch, and between the two we have overcome the over-voltage effect, but we do not know whether the trouble has been cleared by the surge diverters or the air-blast switch.

The impulse flashover voltages for 110kV lines is given in Table 3 as 1 130–1 330kV for wood-pole lines. From this it would appear that co-ordination of insulation should start at the overhead line and end at the transformer windings. This would seem to be reasonable, since damage to overhead lines takes a long time to repair, involving line patrols, arrangements for removing the line, etc., but except with broken conductors, there is generally no urgency in commencing the repair. Has the insertion of a weak link in the line ever been tried? A method would be to have the poles adjacent to the stations provided with lower insulation than the rest of the line, and therefore they would act as another line of defence to the station.

Has the author any information about electricity undertakings purchasing reduced-insulation-level transformers plus surge diverters in order to save money on capital equipment? The trend seems to be to purchase transformers of the full insulation level, have them impulse-tested, and then, after making certain the transformer will theoretically stand up to all expected conditions, to erect surge diverters to make things doubly safe. I can see such a saving being effected in switchgear, but not in transformers.

The author states that it is more serious to have a breakdown on the switchgear and busbars than on a single transformer on systems of 132kV and above. This is true if the more important consideration is the loss of the output of the station rather than the loss of the equipment. I believe that the loss of a transformer is the most serious one which can be incurred. Switchgear can often be bridged or replaced in a very short time. The loss of a transformer can be felt for a very long time. Interconnection and transfer of load, if possible, can, of course, counteract the loss of a transformer.

Mr. A. Burke: The clearances given in Table 13 are presumably based on a bad case, and hence are unnecessarily large for most positions.

Manufacturers have succeeded in continuously reducing the size and hence the cost of transformers, switchgear, etc., while maintaining and even improving the performance. It seems that there is a need to determine and tabulate more precisely the

* CLARK, F. M.: "The Role of Dissolved Gases in determining the Behaviour of Mineral Insulating Oils," *Journal of the Franklin Institute*, 1933, **215**, p. 39.
WATSON, P. K., and HIGHAM, J. B.: "Electric Breakdown of Transformer Oil," *Proceedings I.E.E.*, Paper No. 1501 M, March, 1953 (**100**, Part IIA, p. 168).

relation between the breakdown values of air clearances under a variety of typical conditions so that similar economies can be made in space and structures. Can the author give impulse breakdown values for the following or similar cases?

(*a*) Between parallel circular conductors, with remarks on the influence of stranding, radius, and the presence of other conductors.

(*b*) Between two straight circular conductors, one being in a plane at right angles to the other.

(*c*) Between the heel of an angle iron and a bent circular conductor in a plane at right angles to the angle iron, with remarks on the influence of the radius of curvature, the direction of curvature, and the position (vertical or horizontal) of the angle iron. (This case arises when jumpering under a cross-arm or around a mast.)

(*d*) Between a circular conductor and a plane to which it is parallel, with remarks on the influence of

(i) Direction (vertical or horizontal).

(ii) The substitution of an open-link mesh for the plane, or the presence of continuous projections from the plane (such as the flange of an angle iron) or of localized projections (such as a bolt head).

Mr. H. Montgomery: I am interested in the protection of small single-phase rural transformers on unearthed 10kV lines. There are about 15 000 of these transformers of 3, 5 and 15kVA capacity in commission, and when the rural electrification scheme is complete we expect to have 50 000. All these transformers are purchased to impulse-tested designs, but it was noticed that some designs withstood lightning better, although all the designs had passed the same impulse tests. It was thought that this was probably due to the type of bushings used, which permitted external flashover rather than failure of the windings. As a result, all transformers are now fitted with rod-gaps to allow flashover below the 95kV impulse-test value. The basic insulation levels of a representative transformer obtained on impulse test are as follows:

Rod-gap	70kV
Bushings	120kV
Windings	better than 150kV

Unfortunately, we still get failures as a result of lightning. During 1952 there were about 80 failures out of a total of about 12 000 transformers in commission. In some cases the gaps have been effective and transformers are reported as being still in commission although the tips of the rod-gaps are burned away. We should like, if possible, to reduce the number of failures; however, the percentage is small and it would not be economic to spend more money on protection. Can the author give advice on what further protection could be economically adopted? No values are given in Table 4 for anything under 5in. The gaps we are using to give 70kV flashover on impulse tests are a single gap of 3in or two 1in gaps in series.

Mr. W. P. Leech: I query the assignment of a 650kV breakdown level (as shown in Fig. 1) to the internal insulation of transformers designed to a 550kV withstand level and proved only to that level for full-wave impulses. I regard it as unsafe to base insulation co-ordination on a 50% breakdown value for the transformer of much more than 550kV.

Regarding surge-diverter tests, some test should be specified as an assurance of the diverter's ability to handle switching surges, since these may represent a more severe duty than the standard 10/20 microsec wave.

In spite of what has been said, surge diverters are not necessarily the answer to surge problems, particularly on arc-suppression-coil earthed systems and in low lightning areas. They are expensive, their characteristics may be adversely affected by accumulation of moisture or leakage of gas, and they cannot readily be examined. The rod-gap, on the other hand, is very simple, it is cheap and it is open to visual inspection.

Its main disadvantages on an extinguished system are its poor voltage/time characteristic and its polarity dependence. The former can be overcome by shielding a section of incoming line to prevent waves of more than a certain steepness from reaching the transformer; even with surge diverters this might be advisable, in order to limit the discharge current to a safe value. The question of polarity dependence on large gap spacings could probably be largely overcome given some co-operation from the manufacturers. Several factors which influence polarity dependence are subject to control, e.g. the closeness of the tank cover to the lower electrode, the shape of the electrodes, the closeness of the through conductor in the bushing, etc., and it should be possible to control these factors to such an extent as practically to eliminate this disparity. One Continental switchgear manufacturer has, in fact, succeeded in doing this, but in general, transformer manufacturers do not appear to have devoted a great deal of attention to the problem. Manufacturers are ready to insist on maximum rod-gap settings (frequently based on figures for an ideal rod-gap in the horizontal plane, and far removed from extraneous influences). They should do some work on the development of rod-gaps which are virtually independent of polarity, so that transformers could be supplied with properly co-ordinated rod-gaps which would not flash over for switching surges below an agreed amplitude.

Dr. R. C. Cuffe: The principle of basing protective levels of systems of 52kV rating and above on the residual voltage corresponding to 5kA arrester discharges appears to be more or less generally accepted, and there seem to be good grounds for not taking larger discharge currents. For systems with lower rated voltages, the proposal to take the much higher value of 20kA seems technically not so easily justifiable.

First, can the author state whether field records of arrester discharge currents from such lower-rated voltage systems show a higher incidence of large discharges than on high-voltage systems?

Secondly, on the question of insulation co-ordination and lightning protection, a point often overlooked is the protective value of having more than one line connected to a busbar; this refers especially to transformers. The parallel paths for lightning surges substantially reduce the surge voltages impinging on the transformers. Frequently on lower-voltage systems a number of lines are fed from the same busbar, and hence an insulation level based on 5kA discharges should be adequate.

The contention in Section 2.3 that, for strokes occurring very near to the station on lines without earth wires, the entire current of the stroke may have to be discharged, is rather hard to follow. The author mentions in Section 2.2.2 that the current of a stroke divides and flows in each direction along the line. This would appear to hold good in all cases.

The spacing given in Table 13 appears to be excessive; in Ireland for many years some stations on the 110kV system (arc-suppression-coil earthing), having incoming lines without overhead earth wires, have been successfully operated with minimum clearances as low as 39in. Even with these low values no trouble has been experienced from flashover.

[The author's reply to the above discussion will be found on page 262.]

NORTH STAFFORDSHIRE SUB-CENTRE, AT STAFFORD, 18TH DECEMBER, 1953

Mr. S. E. Newman: In addition to lightning strokes, insulation is subjected to internally produced over-voltages, and in Section 2.2.1 the author gives some over-voltage factors. Transformer and line-switching tests have recently been carried out at West Melton on the B.E.A. 275kV section between West Melton and Staythorpe, and the maximum over-voltage factor obtained was a little over 2.

Referring to Section 3.3, where a cable is connected to an overhead line, wave reflection takes place at the ends of the line and cable, and the possible over-voltage at the end of the cable is dependent upon the cable length. Can the author give any guide as to the minimum length of cable which should be employed?

Referring to Section 3.3.1, I think the author will agree that where a diverter is mounted directly on a transformer the figure of 30kV can be disregarded, since this is intended to cover the voltage drop in the dropper connection and earth leads.

In Section 3.3.2 mention is made of a 900kV insulation level on a 245kV system. The Bonneville Power Authority are now using 825kV circuit-breakers on their 220kV (nominal) system.

Referring to Section 3.6, a transformer failure can result in a far more prolonged and costly outage than a busbar flashover in air, and for this reason it is common practice to mount surge diverters at, or preferably on, the transformer. On an effectively earthed system it is permissible to use a lower insulation level both for switchgear and transformers, provided that the over-voltage protection is correctly selected; surely the argument for a lower insulation level on the transformers than on the switchgear is the relatively large saving in cost of the transformers as compared with the saving which may be possible on the switchgear.

In the second paragraph of this Section is not the word "may" somewhat misleading, since a surge diverter does, in fact, give a degree of protection over a distance from it in both directions.

Mr. D. H. Ryder: Fig. 1 shows various breakdown-voltage/time-lag characteristics. In practice, each curve has a certain amount of scatter as well as a change owing to atmospheric conditions.

In Sections 3.5 and 3.6 it is suggested that switchgear, transformers and transformer bushings should have graded strengths within the substation, the transformer bushings being the weakest and the switchgear being the strongest. In view of the scatter in Fig. 1 and also the possible change of transformer strength with time, I consider it more realistic to reduce the number of insulation levels to a minimum, so that the discrimination between levels is increased.

If it is required to discriminate between points of breakdown in the substation when the protective rod-gap or surge diverter fails to limit the surge voltage, this is best achieved by installing rod-gaps at the transformer and switchgear terminals. The flashover of such rod-gaps would be much more reliable than that of a transformer bushing or transformer internal insulation. A further justification for fitting such protective gaps is the small margin existing between diverter residual voltages and the equipment insulation levels in the case of the highest system voltages.

Mr. J. W. Gibson: The over-voltage requirements for fuses, quoted in Table 2 of the paper, can readily be met using modern current-limiting powder-filled h.r.c. fuses. Furthermore, it is characteristic of such fuses that the generated over-voltages decrease progressively with decrease in fault current, so that one has an assurance that a fuse which has been proved satisfactory from this point of view by breaking-capacity tests at full apparent power will also be satisfactory under service conditions. With circuit-breakers, where over-voltages occur principally as a result of the chopping of small currents at low power factor, it would appear impracticable to obtain a similar assurance on the basis of the usual breaking-capacity tests. How would the author propose to overcome this difficulty?

[The author's reply to the above discussion will be found on page 262.]

NORTH-WESTERN CENTRE, AT MANCHESTER, 5TH JANUARY, 1954

Mr. E. Oldale: I am concerned only with voltages of 33kV and below, but the problem of the co-ordination of insulation is still present, as surges arise causing damage which may be less spectacular in its effect than at the high voltages but is still undesirable. The author rightly stresses the importance of the phase–earth voltage which may arise and its relation to the system earth employed. In Section 2.2.1 it is indicated that with internal surges on earth-neutral systems the over-voltage factor did not exceed 3, and in this connection it may be of interest to note that in some recent tests made by the E.R.A. on an extensive 33kV network in this vicinity a maximum figure of 2·67 was recorded.

Most of the sources of internally-produced over-voltages are mentioned, but it may be noted that voltages of up to 90kV were experienced on the 33kV busbars of a power station not far from here on the occurrence of earth faults on the system. Arresters were fitted, but these have on occasions disintegrated, presumably owing to the characteristics of the wave which arises under these conditions.

The author states that rod-gaps, expulsion gaps or surge diverters may be used as over-voltage protection against lightning surges, but he indicates a preference for the latter. However, reference to Dr. Forrest's paper* shows that with rod-expulsion-gap protection the fault incidence for 132 and 33kV transformers is 0·28 per 100, and it should be borne in mind that this figure relates to many transformers of older designs. In America it is estimated that the impulse level of transformers rose between 1910 and 1930 from 50 to 65% of the present value, and between 1930 and 1940 to the present level without the use of more materials; no doubt comparable figures could be produced by British manufacturers.

The author states that expulsion gaps are not considered to be adequate protection for transformers other than those rated at 15kV or less, which appears to conflict with a statement by Dr. Forrest that expulsion gaps protected by porcelain shrouds were standard protection on the British Grid for 33kV transformers. Presumably the provision of such a porcelain shroud would make the unit almost as expensive as a diverter, and it would therefore be preferable to use the latter, which does not suffer from the limitations of the expulsion gap.

On distribution systems there is a tendency to use unearthed construction on overhead lines for voltages up to 33kV, utilizing wood-pole supports in preference to steel towers. Doubtless such lines are subject to induced lightning surges rather than direct strokes, but the impulse level of such lines is much higher than the steel-tower line, and unless steps are taken to protect terminal apparatus considerable damage may result. It is my experience that where arresters are not fitted the cable from the sealing end is frequently punctured below the wipe, no doubt owing to slight drainage of compound.

On 11kV lines, however, it is not economic to fit diverters at

* See Reference 21 of the paper.

each transformer position. Duplex gaps are fitted on pole-mounted transformers, and on the occasion of a flashover a fuse blows. The replacement of such fuses is, however, expensive in time and material, and the present tendency appears to be to fit one set of diverters to cover a number of pole-mounted transformers; it is anticipated that this will reduce the number of blown fuses appreciably.

Difficulty arises in obtaining data relating to the operation of arresters, and the provision of surge counters was relatively expensive in the past. However, a new and cheaper unit, based on the klydonograph principle, has been developed recently; it indicates not only the frequency of operation but also the magnitude of the surges dealt with.

Table 9, which is based on the peak value of over-voltages arising from high-voltage fuse operation, is of interest when compared with B.S. 116: 1952, particularly for 3·3kV cable. It would appear that if the values in the Table are based on correct premises, the figures in B.S. 116 are in need of revision.

On the Continent it is the practice to stipulate that the 50c/s test voltage shall be a fixed proportion of the impulse level of the particular gear, and I would like the author's opinion as to the advisability of this provision.

It is unfortunate that in B.S. 116: 1952 no impulse level is stipulated for switchgear for use at voltages below 22kV, and difficulty arises in co-ordinating insulation levels at these voltages Does the author think it desirable that impulse levels should also be laid down for 11 and 6·6kV switchgear?

In E.R.A. Report Ref. S/T62 some indication was given of the measure of protection from lightning surges which could be obtained by installing various lengths of cable between an overhead line and switchgear. Is there any evidence to substantiate the figures given in this Report, and would it not be better, where the cable lengths are relatively short, to ignore the effect of the cable capacitance when considering schemes for the protection of the substation equipment?

Mr. W. H. Thompson: In referring to capacitance switching the author states that, if a circuit-breaker opens on an unloaded line and no restrike occurs, the line will be de-energized, but that if there is a restrike, an oscillation will start at one-quarter of the wave frequency. Before the circuit-breaker opens the unloaded line is being charged at, say, $I_x$amp. When the circuit-breaker has opened and the fuss of interruption has subsided, the line is still being charged, but at a very much lower rate, say $I_y$amp, because of the series capacitance of the circuit-breaker. It is this sudden change from I_x to $I_y$amp that causes the system on each side of the circuit-breaker to oscillate at the natural frequency of each side. The voltage across the circuit-breaker at any instant is equal to the difference in voltage between these two oscillations at that instant. There will be a number of restrikes within the first half millisecond after arc extinction, and the line may be left at more than the phase peak voltage, etc.

In Fig. 1 the curves can represent only the mean values of a wide scatter of results. In practice, these curves would be replaced by a series of bands, which would overlap each other to such an extent that the degree of co-ordination would not be so precise as implied by Fig. 1. This does not mean that co-ordination is not possible. It is possible and desirable, but unavoidably it can be no more than a coarse relationship of values.

Because of this practical limitation, it is surprising that so much controversy should exist on earth-clearance values. For a 132kV system the author quotes 53in. Another paper quotes the figure of 54in, and according to tests made at a high-voltage laboratory in this country, the value should be 55in. The Central Electricity Board used a clearance of 48in or less, and no case has been reported of a flashover on such a clearance. I suggest that the author might agree to a compromise of between 48 and 53in, and I support a recommendation of 50in.

Mr. E. T. Norris: Table 10, which is the basis of the paper, is superficially very satisfactory, but depends upon arbitrary values for modern surge-diverter performance. Considering for example the 132kV-Grid values, the protection level of 519kV against a basic insulation level of 550kV seems reasonably satisfactory. Should not the protection level take account of the 50c/s voltage at the instant of the surge? This may occur on the opposite polarity of the surge, and there is a 1 : 7 chance of its being within 10% of the maximum value, which is not a negligible risk and would increase the protection level from 519 to 640kV, compared with an insulation level of 550kV.

In Section 2.3 it is stated that 4% of the strokes are over 5 000amp, and these are ignored. I think it would be logical to consider this 4% which will do the damage, and ignore the 96%, which are relatively harmless. If we assume lightning strokes of 10 000amp the protection level increases to 710kV, which does not seem at all satisfactory compared with the 550kV insulation level.

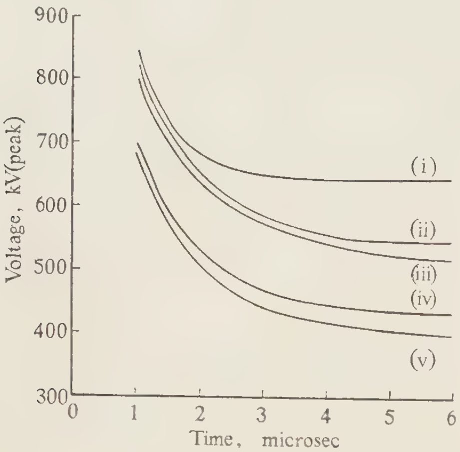
The protection afforded by rod-gaps is not really known, because, unless a power arc follows—which is not probable—there is no indication to the operating engineer of rod-gap operation. Would the author suggest that with modern reclosing circuit-breakers, where momentary interruptions are unobjectionable, rod-gap settings could be considerably reduced so as to give much greater protection?

Mr. L. C. Richards: In Fig. 1 the author gives a number of voltage/time characteristics, among which are curves showing the estimated breakdown characteristics of a transformer having a full-wave withstand voltage of 550kV and a chopped-wave withstand voltage of 630kV, i.e. a typical 132kV transformer having the neutral point solidly and permanently earthed. Another curve shows the characteristics of a 26in rod-gap, and by comparison it is concluded that, for time lags greater than 2microsec, such a gap gives adequate protection.

I think that the idea of designing a system of protection on the basis of the estimated breakdown of a transformer is entirely wrong. A transformer is designed to withstand a certain impulse voltage, and no figures for breakdown should be given either as a guide or a guarantee. The difference between the withstand voltage and the ultimate breakdown voltage is the designer's margin, which is required in order to cover inequalities in materials and building factors and so ensure that the withstand value can always be met.

It is interesting to note that British transformer manufacturers have recently prepared a draft specification dealing with insulation levels and test procedure in which an appropriate withstand test level is proposed for each system voltage. It is stated that the design of the system and the method of operation should be such as to ensure that any transmission surges which reach the transformer are appreciably less than the insulation test level. A further clause states that the amplitude of the travelling waves reaching the transformer terminals should be limited to a value not exceeding 80% of the impulse test level of the windings, and that suitable protective devices should be used for this purpose.

Curve (i) of Fig. E is curve (*c*) of Fig. 1 of the paper, and is the author's estimate of the breakdown of the transformer. Curve (*e*) is reproduced as curve (iii) and is stated to give adequate protection for time lags greater than 2microsec when there is a reasonable space between curves (ii) and (iii); but I cannot agree with this, since the position of curve (ii) is quite indeterminate. Curve (iii) represents a more reliable foundation on which to base a protective system. 550kV is the amplitude of the guaranteed withstand voltage, and 880kV is a reasonable assumption for the withstand voltage at 1microsec. The 80% level to which the



ig. E.—Insulation co-ordination for a 132kV transformer 550kV impulse level.

(i) Assumed transformer breakdown.
(ii) Transformer withstand level.
(iii) 26 in-gap flashover.
(iv) 80% transformer withstand level.
(v) 22 in-gap flashover.

rotective gap should limit surges is shown in curve (iv), and the 2in gap, which would itself adequately protect a transformer, ives an almost identical curve. My contention is therefore that, or the case envisaged and where the gap is the only means of rotection provided, it should be 22in and not 26in.

The fact that the British 132-kV Grid system operates satis- actorily with 26in gaps in no way vitiates the above argument, nce, first, this country is not in any sense of the word a lightning rea and therefore the system is not subjected to serious surge onditions, and secondly, the approach lines and the substations nemselves are well protected by overhead earth wires and ther devices.

Mr. W. A. McNeill: Referring to Tables 10 and 11, I find it ery difficult to accept the justification for different test levels Europe and America for the lower system voltages. It has bviously been impossible to reconcile two different points of ew. However, British manufacturers will have to meet the merican standards in oversea markets, and I believe that the gher level will prevail. I do not see any difficulty in providing e required insulation level for outdoor switchgear.

The problem is rather more complex when applied to indoor uipment. I agree with the author's statement that the standard min power-frequency test provides a satisfactory margin for the ual switching over-voltages experienced on cable networks, it it may well be asked, what is a usual switching over- oltage? It depends on a number of factors, including the pe and design of the interrupting device, the nature and value the load, and the characteristics of the circuit. It is known at some circuit conditions and certain types of circuit-breaker ay produce high over-voltages. The maximum voltage will only ise when these extreme conditions occur together. Even under ese circumstances, the likelihood of the highest transient ltage occurring on any one switching operation is a subject statistical analysis.

Because of the number of variables it is very difficult to specify ceptance tests to cover all conditions, and it does not seem ssible, at present, to agree upon a Table of limiting values for types of circuit-breaker. There is little doubt, however, that nufacturers will give increasing attention to this problem. number of investigations have already been carried out, both short-circuit laboratories and in the field. From the data available, I agree that the maximum over-voltage factor will rarely exceed 3, for earthed neutral systems.

With these considerations in mind and taking account of service experience, I agree that impulse-voltage tests are unneces- sary for equipment connected to cable networks. Unfortunately, however, such tests are often specified by customers. The problem resolves itself into a question of economics. Some standard designs of indoor unit may have levels as high as the equivalent outdoor circuit-breaker, but when allowance is made for the various ancillary components, such as voltage trans- formers, current transformers, additional cable boxes, etc., which may have to be accommodated on each contract, it is not always possible to maintain the same level. The cost of increasing the insulation level may be much greater than indicated in the paper, if due allowance is made for design and development costs and for the high capital cost of new jigs and fixtures. This must ultimately be borne by the consumer.

Mr. A. Raven: An outstanding point in the paper is the recommendation that the co-ordination of insulation be made against the surge-diverter residual voltage as a standard. Whereas insulation in its many forms is subject to extensive specifications, the surge diverter is not yet the subject of a British Standard. If the author's opinions are correct—and with modern surge-diverter equipment there is every indication that the approach is sound—it implies that there is an urgent necessity for a British Standard on surge diverters.

At the lower voltages usually associated with wood-pole lines, and therefore a large number of insulation positions, this approach is not valid, except possibly for unearthed-line construction at 33kV, where the number of earthed positions is relatively small. Most of these lower-voltage lines were constructed with no attempt at overall co-ordination of insulation, and the overhead lines were often over-insulated, e.g. 22kV insulators were common on 11kV lines. From present-day statistics it is known that at least 75% of overhead-line circuit interruptions can be successfully reclosed, the interruptions being due to insulation flashover without persistent damage. Therefore, if lines which were originally over-insulated have insulation flashover after being exposed to a soiling atmosphere, any surge diverters con- nected to the lines would be limited in operation, and moreover, line insulators designed on the basis of the residual voltage of these arresters would have given considerably more trouble under lightning conditions than the type actually used, even to the extent of causing breakdown of supply with the smallest of periodic salt deposits which can affect overhead lines at a considerable distance from the coast.

The principles outlined in the paper can therefore be applied, subject to reliable surge diverters, when insulator cleaning can be organized. This normally means lines with long spans and therefore few insulation positions per mile, or unearthed lines with a small number of earthed positions, such as pole-transformer connections and cable-termination positions.

Co-ordination of insulation on individual units of switchgear and transformers is, of course, necessary, even if it is not always possible to include the line insulation in an overall scheme. If surge diverters are used to protect these switchgear units and transformers, they can be used as a standard for the insulation levels proposed.

Mr. J. E. L. Robinson: For the several arrangements shown in Fig. 1, curves (*a*)–(*f*) show the relationship between breakdown voltage and time to breakdown over a range of 1/50microsec applied impulses. In all these cases the impulse-ratio effect is shown by the rising nature of the curves for decreasing times to breakdown. Clearly, however, curves (*g*) and (*h*) are plotted on an entirely different basis and are in no way comparable. They each represent, under the conditions stated, the waveform

resulting from application to a surge diverter of a single 1/50 microsec impulse, and not, as in the other curves, the characteristics for a family of such applied impulses. If the author wishes to pursue the comparison of the surge diverter with the other devices he must do so on the basis of like characteristics. The corresponding surge-diverter curves would then also show a continuously rising tendency with decreasing time, although, because of the nature of the surge-diverter gaps, it would be expected that the impulse-ratio effect would be much less than, for example, that of the rod-gaps.

The author cites curves (*c*) and (*d*) as being representative of the breakdown strength of transformers. They are certainly not representative of transformers as I know them. For the purpose of his argument it is understandable that he wishes to indicate something typical of the withstand level of transformer insulation. The curves, although not of the right amplitude, have the characteristic shape for transformer major insulation. However, they represent an over-simplification of the conditions, since they do not represent the strength of the axial insulation, which is the factor that usually determines the impulse strength of the transformer.

[The author's reply to the above discussion will be found on page 262.]

NORTH-EASTERN CENTRE, AT NEWCASTLE UPON TYNE, 22ND FEBRUARY, 1954

Mr. J. F. Bird: Two of the main factors used by the author to reach his conclusions are the over-voltages which may be expected from h.v. fuses and the performance of lightning-protection tubes and surge diverters. In stressing the importance of these items, he has tended to overlook other factors which can be considerably more important.

With regard to over-voltages, a list of values is given in Table 2 relating to h.v. fuses. So far as I know, high-voltage power fuses are not generally available at many of the voltages included in this range. Therefore the values quoted for the higher-voltage ratings must either be somewhat tentative, or they must have been derived from voltage-transformer fuses. In neither case is this a satisfactory way to approach the problem of over-voltages produced in switching, since the phenomena involved are entirely different.

With regard to the performance of protective gaps and surge diverters, it can be seen that curve (*h*) of Fig. 1 is presented as the voltage characteristic of a surge diverter. This must be the residual voltage characteristic, since the impulse breakdown characteristic could not possibly drop to zero in the manner shown. Although the residual voltage characteristic is probably the most important factor in assessing the protection level of surge diverters, I cannot accept that this alone can provide an adequate basis for co-ordination. The only proper basis must, of necessity, be a combination of the impulse characteristic (which is important at the shorter times) and the residual voltage characteristic.

The author indicates that the impulse characteristic of rod-gaps is uncertain below 2 microsec, and argues from this that they must be generally unsatisfactory for co-ordination purposes. I cannot accept this conclusion, at least where the higher voltages are involved. At 66 kV and above, the author has himself stated that induced lightning strokes are unlikely to be a source of trouble. Also, where an efficient earth-wire system is installed, direct strokes to the lines are improbable. At these higher voltages, therefore, the main requirement is protection against switching over-voltage. These are generally much less steep-fronted than lightning surges (the author mentions a 20 microsec wavefront), and in this time range, rod-gaps can be satisfactory. This is borne out by satisfactory experience in this country.

At the other end of the scale the author argues that, because cable networks are not subjected to lightning but only to switching over-voltages, impulse-tested equipment is not necessary. A case is presented for 50 c/s testing only, based on a rather indeterminate factor of 1·25 which is stated to relate the switching-surge over-voltage breakdown to the peak 50 c/s breakdown voltage. This generalization is equivalent to stating that, if the insulation is co-ordinated at 50 c/s, the performance with more steeply-rising voltages will also be satisfactory. In effect, it assumes that the breakdown characteristics of all gaps and insulation are of the same shape; this hardly seems warranted. Furthermore, nearly all types of gear installed on cable networks are liable to be located at some time in exposed, or at least semi-exposed, positions. This is a further strong argument for the impulse-testing of these gears.

Mr. W. J. Brown: Since the insulation must satisfactorily withstand the voltage stresses which may be applied to it in service, it is of great importance for the designer to know, as exactly as possible, what the stresses are. The agreement to limit the maximum system voltage to the values given in Table 1 is valuable in that it fixes one of the design parameters.

In considering particularly bushing insulators, it is the maximum system voltage which determines the radial thickness of insulation and consequently the bushing diameter; this is because of the vital necessity to avoid internal ionization at normal operating-voltage levels. The life of a bushing varies inversely as the ratio of the continuously applied voltage to the ionization extinction voltage, as shown in Fig. F. If this ratio is made equal to or less than unity the presumption is that internal ionization will never occur, and except for over-voltages, the life of a bushing will be infinitely long.

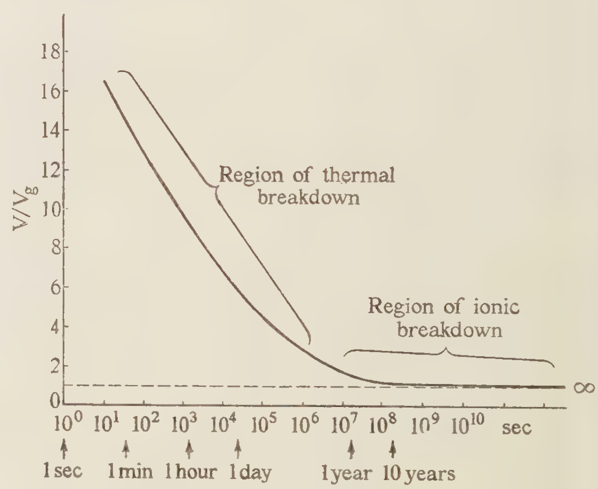


Fig. F.—Expectation of life on condenser bushing insulators.
V = Continuously applied voltage.
V_g = Ionization extinction voltage.

Modern design techniques enable the minimum ionization extinction voltage to be predetermined, and a method of measuring the actual extinction voltage is being developed which is more sensitive than the present standard method, which depends upon the interpretation of the power-factor/voltage curve.

With regard to over-voltages, it has long been the general practice to design a bushing so that the external air flashover

voltage is lower than the internal breakdown voltage. Such a bushing is termed "self co-ordinated." B.S. 223: 1931 requires this characteristic to be demonstrated by actual flashover tests.

Modern ideas now being embodied in the revised edition of this Standard follow a different principle. It is presumed that the system engineer will limit the over-voltages to a predetermined level by means of protective devices. Actual flashover tests will not be carried out; instead, withstand tests will be applied in order to demonstrate that the impulse level of the bushing is high enough to withstand all surges which the protective device allows to pass.

Since it is presumed that no over-voltage higher than the impulse level can ever be applied to the apparatus, it is clear that it is no longer necessary for a bushing to be self-protected; whether it will be wise to take advantage of this is a matter of opinion.

By the installation of surge diverters, adequate over-voltage protection can be achieved; however, there are many installations where, for economic reasons, surge diverters are not used and reliance is placed upon rod-gaps. The impulse-breakdown time delay of a rod-gap is longer than that of solid insulation of similar electric strength, and so it is clear that a steep-fronted wave may damage the insulation before it is chopped by the gap unless the electric strength of the insulation is greater than that of the gap.

Mr. G. H. Hickling: In Section 2.3, referring to Fig. 1, the author discusses the relative merits of the rod-gap and the surge diverter as the two principal devices for over-voltage protection. His comparison is based essentially on the breakdown time-lag characteristics which are represented in the graph. A most important characteristic of the rod-gap so far as transformer protection is concerned, which is overlooked in the paper, is its property of generating chopped voltage waves. In the typical case assumed in current-impulse test specifications, chopping occurs from 115% of the specified full-wave test level, and it takes place in a time very much shorter than the wavefront time—frequently under $\frac{1}{2}$ microsec. Whilst exact values which would be generally applicable cannot be given, an average transformer will have a safe impulse test level about 50% greater for full-wave impulses than for chopped waves, assuming sufficient insulation to earth. This factor accrues in part from the 15% over-voltage occurring in the latter case, but mainly from the severe inter-coil stresses caused by the rapid collapse of voltage. Surge-diverter protection, by eliminating this condition, would thus make possible a very real saving in inter-coil and inter-turn insulation.

The general adoption in this country of rod-gap protection for transformer substations, reflected in impulse test specifications by the inclusion of the chopped-wave test, is a factor both of national and international importance at the present time. At C.I.G.R.É. in Paris in 1952, it was made clear that the majority of European countries declined, on various grounds, to accept any impulse test other than the 1/50 microsec full-wave one as a commercial acceptance test for transformers, chopped-wave testing being restricted to research work. Only Great Britain and the United States—and with some reservations, France—accepted the complete full-wave and chopped-wave test. It follows that the British manufacturer is at a definite disadvantage in the international market for impulse-tested transformers. A decision on this aspect of British transmission-system design for the future would consequently be of value alike to the manufacturer and to those responsible for the standardization of test specifications.

Mr. R. A. Hore: The magnitude of switching over-voltages may make it difficult to use rod-gaps for co-ordination, since it is undesirable for rod-gaps to flash over on such over-voltages because of the possibility of subsequent power follow-through. With oil circuit-breakers, the sudden pulse of short-circuit current through a pot full of oil is likely to result in damage. With air-blast circuit-breakers, if restriking continues until after the series isolator arm has started to open and a rod-gap flashes over with power follow-through, the subsequent short-circuit may cause a long arc to be drawn by the series isolator, which may lead to a busbar fault.

Taking a 132 kV system as an example, if the over-voltage factor can reach 3·5, this fixes a minimum setting for the rod-gap of about 32 in (50 c/s wet value). The frequency of the switching surge is almost invariably so low that flashover voltages are substantially the same as at 50 c/s. A 32 in rod-gap has an impulse flashover voltage of about 530 kV. It is clear, therefore, that if due allowance is to be made for the rather erratic performance of rod-gaps, switching over-voltage factors in excess of about 3·2 on 132 kV systems make protection at an impulse level of 550 kV by means of rod-gaps difficult and sometimes impossible.

The protection of apparatus by lengths of cable is only effective against lightning strokes at a distance from the cable–line termination; surges originating near the termination enter the cable substantially without reduction by reflection at the junction. Therefore, if we consider the chances of lightning strikes to the line over, say, the first mile to be serious, this length of line should be shielded.

In fact, any cable or cable system connected to overhead lines is exposed to lightning to the same extent as the portion of the line adjacent to the terminations; and the number of direct strokes to which the cable or cable system is exposed may be assumed to be approximately the same as the number of strokes which may be expected on, say, the first mile of overhead line at each termination multiplied by the number of such terminations.

Much of the insulation co-ordination is based on the statistical data of transformer failures. I suggest that this should be presented as "the percentage transformer kVA damaged," rather than as "the number of transformers damaged per hundred on the system." Often the latter figure leads one to suspect that surge diverters should be more widely used, until one finds that the majority of the failures are on small pole-mounted transformers for which the cost of protective equipment would be of the same order as the cost of the transformer.

Mr. D. Riach: The 1 min power-frequency test voltages, prescribed as minimum values by the I.E.C. and listed in Table 9, are approximately the same as those prescribed in the relevant British Standards for switchgear and transformers, but are much higher than those given in B.S. 480 for paper-insulated cables. For instance, for a rated voltage of 22 kV, the test voltage in B.S. 116 for oil circuit-breakers is 52 kV, whereas in B.S. 480 for paper-insulated cables it is only 25·5 kV [36 kV (peak)], although this is for 15 min instead of 1 min. Although experience may indicate that the cable has adequate insulation to withstand the maximum switching over-voltage—in this case 85 kV (peak) according to Table 2—I disagree with the author, particularly in regard to cables, that the present power-frequency test voltages are sufficiently representative of switching over-voltages.

Mr. G. D. Clothier (*communicated*): The author shows that it is possible to co-ordinate insulation with surge-voltage conditions upon a factual basis. This is because it is practicable with modern surge diverters to control the maximum stress to which any vulnerable insulation may be subjected. Accordingly, insulation design and standardization are increasingly based upon surge-diverter performance, and thus it follows that this work might be simplified if the paper could embody recent progress in the development of surge diverters. For example, the performance figures in Table 6 could be much improved, so that the surge-diverter performance level represented by curve (*h*)

of Fig. 1 could now be at 330kV instead of 420kV. As an example towards simplification, the maximum residual voltage can now be substantially the same both at 20 and 5kA, so that the last two columns of Table 6 become identical, and furthermore, there is no need for the insulation designer to worry about a rise in residual voltage with higher surge currents. Incidentally, the two columns might lead one to imagine that a smaller arrester is suitable for station duty than that necessary for line duty, whereas the reverse is the case.

Co-ordination of insulation is so much affected by any decision to use or reject surge diverters that reference to their other uses might assist in reaching conclusions. These uses include the installation of surge diverters at transformers, especially up to 33kV, in order to minimize discontinuity of supply owing to the operation of fuses under transient flashover conditions in lightning storms, at the same time often avoiding the need for fuses and fuse maintenance.

Messrs. R. Bruce and **G. K. Simpson** also contributed to the discussion at Newcastle upon Tyne.

[The author's reply to the above discussion will be found below.]

MERSEY AND NORTH WALES CENTRE, AT CHESTER, 15TH MARCH, 1954

Mr. E. A. Burton: In Section 3.6 it is stated that "It is therefore common practice to have a higher insulation level on the switchgear than on the transformers." The insulation (for power frequencies or impulse voltages) is easier for switchgear than transformers. The power-frequency test voltages for bushings and associated switchgear insulation are usually of such a value that there is no difficulty in meeting the desired impulse levels. The insulation of a transformer is inherently more difficult and the power-frequency test usually lower. A transformer effectively designed to meet its 1 min power-frequency test voltage would have a certain inherent impulse strength. If higher impulse strengths are desired, then, of course, these must be paid for; so that one of the economic features when considering surge diverters would be the difference between the cost of a transformer designed to meet its power-frequency test voltage only plus the cost of a suitable surge diverter, and the cost of a transformer with additional "built in" impulse strength. The higher insulation level on switchgear is due not so much to deliberate design as to the inherent difficulties with transformer insulation.

In Section 2.3 it is stated that protector tubes are not considered to be adequate protection for transformer insulation, except for distribution types rated at 15kV or less. From my own limited experience with porcelain-clad-type tubes, they were quite satisfactory at 33kV.

I assume that the values given in Table 4 were for 1/50 microsec impulse voltages, and that the gaps were standard $\frac{1}{2}$in-square horizontal types.

Table 7 gives minimum creepage distances for various voltages under normally-polluted and heavily-polluted atmospheres. So far as this country is concerned, I feel that all outdoor insulation should provide for heavily-polluted atmospheres.

In Section 2.5 it is stated that under certain conditions of pollution appreciable leakage currents may flow over the surface of the insulation, and that these currents are in the nature of surges. The author states that these currents may affect very considerably the voltage distribution across the insulation. It could be inferred that the current surges cause non-uniform voltage distribution, whereas the reverse is the case. The current surges are the direct result of lack of uniformity of voltage distribution across the insulation.

Mr. R. O. M. Powell: The use of capacitors in the past for the protection of apparatus from transient over-voltages has usually been restricted to traction systems and alternators, in cases where the windings are likely to be exposed to steep-fronted waves. For obvious economic reasons, the capacitances involved have always been small.

The advent of the larger blocks of capacitance used in high-voltage shunt banks suggests that a larger measure of protection is automatically provided to associated equipment under certain conditions. This is especially valuable since the majority of shunt-capacitor installations occur at voltages of the order of 11 and 33kV, and these systems are particularly vulnerable to outages from transient waves. If a capacitor bank is arranged in star, with the neutral earthed, the impedance of the capacitors connected phase–earth is virtually negligible so far as any transient-wave phenomena are concerned. This means that, with wavefronts having rise times of the order that are encountered in practice, apparatus located near the capacitor installation will be completely protected. Where the capacitor bank is connected in delta or unearthed star, the benefits are obviously not so great. Has the author any views on the protective effects of a large capacitor bank connected in this way?

Has the E.R.A. surge filter ever been tried out in practice? It is not only capable of limiting the amplitude, but also has the very desirable property of modifying the steepness of the wavefront.

Mr. R. R. Arnold: The author's comments relating to impulse testing apply mainly to type-testing at a testing station, but I am more interested in *in situ* testing. If switchgear in a substation has been subjected to impulses and over-voltages, one is never sure whether the impulse applied is greater than the impulse level of the equipment. It is probably impracticable to transport impulse-testing apparatus to a substation, but a high-voltage inverted-type Schering bridge can be used in substations for measuring the power factor of bushings. Would the author comment on this method, and state whether such a test would indicate that the bushing had retained its rated impulse level?

THE AUTHOR'S REPLY TO THE ABOVE DISCUSSIONS

Mr. J. S. Cliff (*in reply*): As is to be expected when dealing with a subject which involves the characteristics of many different types of apparatus on which technical improvements are still being made, there is plenty of scope for comment and expression of differing opinions. These are very welcome since the subject of insulation co-ordination is very complex, and while there are certain fundamentals on which it can be based, as outlined in the paper, it is also necessary to take into account factors such as economics, local preferences in system operation, and the probability that the many possible causes of failure will not occur simultaneously. Such items do not always follow the strict laws of nature.

On the question of transient over-voltages produced internally, Messrs. Newman and Oldale confirmed the values put forward in the paper. This is a difficult subject on which to obtain exact data owing to the large number of associated factors and the difficulty of deciding whether the worst combination has been examined.

The over-voltage factors in Table 2 have only been taken as representative of the maximum values to be expected up to 33kV.

At higher voltages the over-voltages for fuses are less than those due to other causes, so that they are no longer satisfactory as a basis for determining the insulation level, and are not, in the paper, used for this purpose, as inferred by Mr. Bird.

Messrs. Bird and Boyd question the range of fuses available. The values in Table 2 were taken from a draft British Standard for h.v. fuses, and in fact, power fuses are available for ratings up to 132kV, although the majority are used at voltages below 33kV.

The question of over-voltage protection inevitably raised considerable comment. Mr. Hardaker defends the use of the rod-gap on 132kV transformers in this country, and for my comments on this, I would refer him to my reply to Mr. Lane in the London discussion. The reason for the damage sustained by the transformer mentioned by Mr. Hardaker is difficult to state precisely without further detailed information, but a possible explanation, unless there was a very close lightning stroke giving a wavefront of less than 2microsec, is that a chopped voltage wave occurred, as mentioned by Mr. Hickling, and the transformer insulation was not adequate for steep-fronted waves.

The advocates of rod-gap protection rely mainly upon the low incidence of lightning in this country and the fact that our important substations have more than one supply. Such conditions are not universal, so that it is necessary to choose as a basis for insulation levels at the higher voltages a protective device which will give satisfactory performance on any system, and so far, the non-linear, resistance type of surge diverter is the only device available at present. Neglecting the inability of the rod-gap to extinguish power follow current, to make it completely suitable for protecting transformers in accordance with the manufacturers' recommendations would necessitate reducing the gap appreciably. Mr. Richards suggests that for a 132kV 550kV-impulse-level transformer adequate protection would necessitate a 22in rod-gap instead of the more usual 26in gap. As shown by Mr. Hore this would almost certainly result in excessive operation of the gap, with the resultant tripping of the circuit by the power follow current in many instances. The effects of such interruptions could be minimized by using auto-reclose circuit-breakers, as suggested by Mr. Norris, but the cost and complication of the relay system necessary to achieve this would, in most instances, be greater than that of installing surge diverters.

Protector tubes overcome cheaply some of the disadvantages of the plain rod-gap, and Messrs. Oldale and Burton mention that they have been used in this country for voltages up to 33kV. This is quite true, but as can be seen by comparing the minimum flashover voltages for the tubes given in Table 5 with the insulation levels given in Table 10, there is no safety margin at the higher voltage ratings. Furthermore, the short-circuit currents which the tubes will safely handle considerably restrict their application on the larger systems. Below 15kV these limitations are not so great.

The occasional misbehaviour of surge diverters was mentioned by several speakers, and this must be viewed in the correct perspective. Engineers appear to have very long memories regarding failures, whereas the successful operation of a device is taken for granted and brings forth no comment. It is quite feasible to make surge diverters which would withstand all the most onerous conditions, even if they occurred simultaneously. The expense of doing this would seldom be justified, so that the economic surge diverter must be a compromise based upon the probability of the worst conditions occurring only very infrequently. The cheaper the diverter the greater is the probability of failure. Bearing in mind the possibilities for misapplication and overloading which can occur, particularly with the smaller diverters, it is surprising how few failures are reported. Modern designs are incorporating better materials, giving increased safety factors and ensuring longer life. Many installations using surge diverters and adequate earth-wire shielding are completely safe against direct lightning strokes, as desired by Mr. Hardaker. An important factor in achieving satisfactory shielding is the lowering of the earthing resistance, mentioned by Mr. Jones. Mr. Parish also gives details of the improvement which can be obtained by shielding. In the end, the economics of the problem usually dictate the ultimate solution.

Mr. Raven points out the necessity for a British Standard for surge diverters. The value of this has not been overlooked either by the users or the manufacturers, and drafts are at present being discussed. The main obstacle to publishing such a Standard has been the fact that considerable development in the performance of these devices is still in progress, and discussions within the I.E.C. have been taking place on the subjects of rating and testing. As a large measure of agreement has been reached by the I.E.C., it should now be possible to base a British Standard on this work. This would include impulse-current tests to simulate both lightning and switching currents, as desired by Mr. Leech, and should do much to ensure a more consistent performance in service.

The trend of modern developments is to reduce the residual voltages of surge diverters, as mentioned by Mr. Clothier, but care must be exercised to ensure that the margin in protection of the equipment is not obtained at the expense of the margin of safety of the surge diverter. The values given in Table 6 are typical of the performance obtainable from surge diverters used during the last 15 years, the service life of which has been well proved, and which have been shown to give satisfactory co-ordination with insulation levels similar to those given in Tables 10 and 11. The lower residual voltages now available give a greater margin of protection on the apparatus insulation, and provided that these surge diverters prove, during the next few years in service, to have a sufficient safety margin themselves, it may ultimately be possible to reduce the insulation level of apparatus accordingly, and so achieve a further saving in cost.

Mr. Powell rightly points out that large capacitor banks, if correctly connected, assist in surge protection, but their cost can seldom be justified on this ground alone. The E.R.A. surge filter, mentioned by Mr. Powell, while satisfactory from a theoretical viewpoint, is not available commercially because of the great cost of the large inductance, if made suitable for handling high short-circuit currents with safety, and the limited short-circuit performance of the expulsion gaps.

Mr. Richards disagrees with my adoption in Fig. 1 of the "estimated minimum breakdown characteristic" for a transformer and proposes instead that the impulse-withstand curve should be used. This he shows in curve (ii) of Fig. E, which appears to be the same as curve (i) of Fig. A in Mr. Rippon's contribution to the London discussion. At 3microsec this transformer will withstand only 580kV, whereas according to the draft British Standard it should withstand 630kV. If the transformer had the correct characteristic, the comparison with the 26in-gap characteristic would be slightly more favourable, but still there would be very little margin between the two curves. By taking the minimum margin between withstand and breakdown values, I have shown that the 26in gap can give reasonable protection in special cases, as has been demonstrated by the performance of the 132kV British Grid. I expect that the transformer manufacturers allow a greater margin than I have, so that in practice the protection is actually better than would be expected from Fig. 1.

Messrs. Robinson and Bird are incorrect in assuming that curves (*g*) and (*h*) of Fig. 1 neglect the effect of possible increase of flashover voltage owing to a very rapidly rising voltage. The

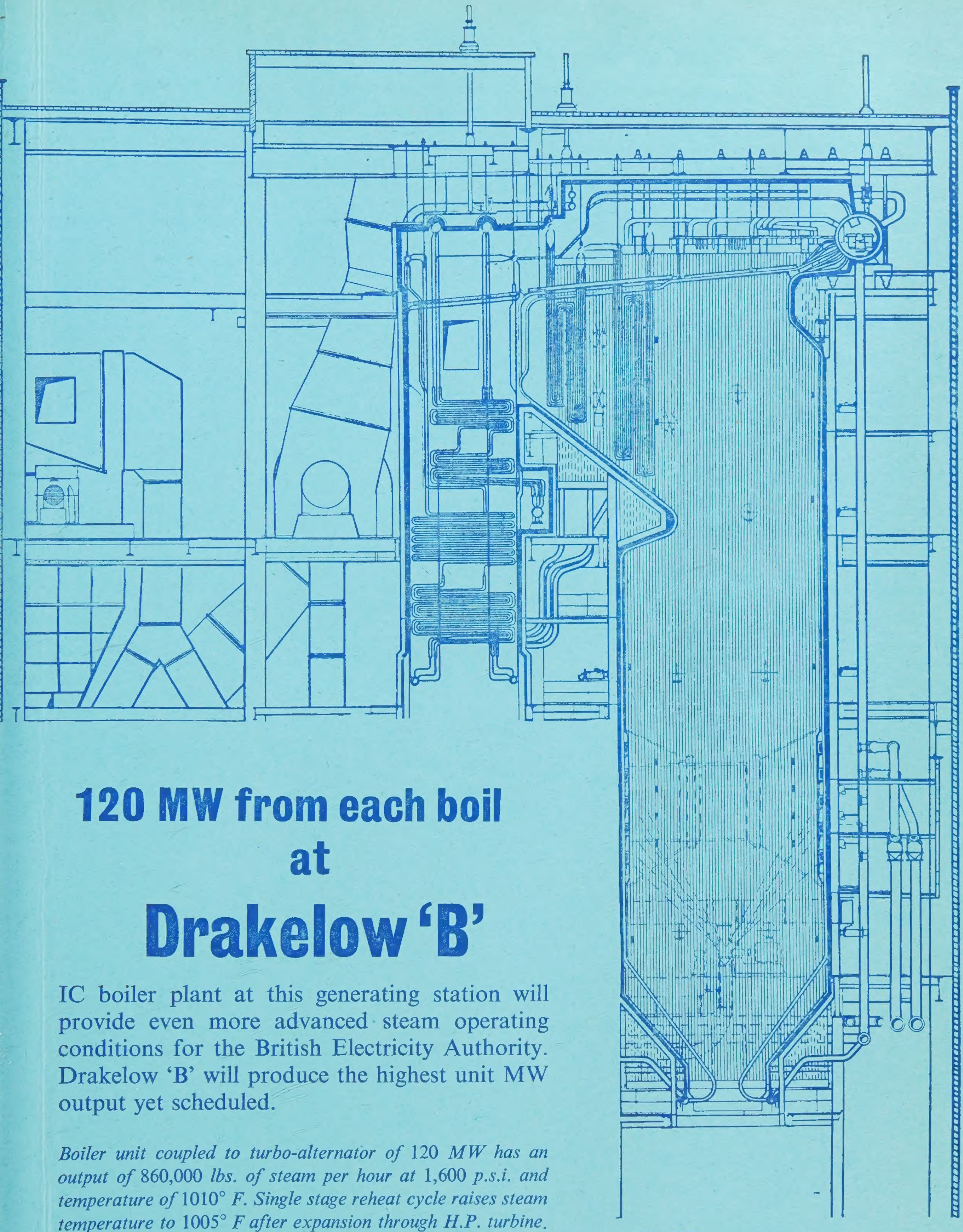
curve shown is a combination of flashover and residual voltage characteristics. Up to 1 microsec the curve follows a surge voltage rising at nearly 500 kV/microsec, which is sufficiently close to the maximum likely to be encountered in service. The peak value of 470 kV attained in curve (*h*) can be compared with the value of 800 kV for a 26 in gap. When the gap flashes over current flows and the voltage in curve (*h*) follows the residual voltage curve, which depends upon the waveshape and amplitude of the current. For this example I have chosen a 5 kA 10/20 microsec wave, since the characteristics of surge diverters for this wave are well known and are reasonably representative of service conditions. In curve (*g*) allowance has been made for some separation between the surge diverter and the transformer, thus giving a higher initial voltage at the transformer terminals before flashover occurs and also allowance for some resistance in the earth connection, which increases the residual voltage at the transformer terminals. In practice, the transition from flashover to residual voltage would take the form of a damped oscillation, the frequency depending upon the inductance of the connection between the surge diverter and the transformer-winding capacitance. Curves (*g*) and (*h*) illustrate very well the advantage of connecting the surge diverter at the terminals of the transformer, as advocated by Messrs. Newman and Boyd. It is difficult in a short space to give satisfactory general guidance on the maximum permissible distance between surge diverter and transformer, as it depends on a number of factors, and details of the particular installation should be sent to the surge-diverter manufacturer for his advice.

Dr. Cuffe and Messrs. Burke and Thompson question the necessity for clearances as large as those given in Table 13. This subject has received considerable attention by committees dealing with specifications, since if the users insist upon a guarantee that the clearances will withstand a specified impulse voltage, the worst case must be assumed pending the compilation of comprehensive data, as requested by Mr. Burke, which at present is not available. On the other hand, it is well known that many installations have operated satisfactorily with smaller clearances, particularly where protective devices are used. Since the paper was written, further study has shown that the values

Table A

Insulation-level impulse voltage	Minimum distance for withstand	Recommended minimum clearance
kV	in	in
150	12	11
200	17	15
250	21	19
350	30	27
450	38	34
550	47	42
650	56	50
750	65	58
900	78	70
1 050	91	82

given in Table A are reasonable; those in the second column cover the worst possible configuration of electrodes, while the third column gives values based on service experience.



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APRIL 1955

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Printed by Unwin Brothers Limited, Woking and London.